AEROSPACE REPORT NO.
ATR-93(3778)-2

A Formal Description of the Incremental Translation of Stage 3 VHDL into State Deltas in SDVS

30 September 1993

Prepared by

I. V. FILIPPENKO
Trusted Computer Systems Department
Computer Science and Technology Subdivision
Computer Systems Division
Engineering and Technology Group

Prepared for

DEPARTMENT OF DEFENSE
Ft. George G. Meade, MD 20744-6000

DTIC QUALITY INSPECTED 2

Engineering and Technology Group

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION IS UNLIMITED

THE AEROSPACE CORPORATION
El Segundo, California

19971001 037

AEROSPACE REPORT NO.
ATR-93(3778)-2

A FORMAL DESCRIPTION OF THE INCREMENTAL TRANSLATION OF STAGE 3 VHDL INTO STATE DELTAS IN SDVS

Prepared by

I. V. FILIPPENKO
Trusted Computer Systems Department
Computer Science and Technology Subdivision
Computer Systems Division
Engineering and Technology Group

30 September 1993

Engineering and Technology Group
THE AEROSPACE CORPORATION
El Segundo, CA 90245-4691

Prepared for

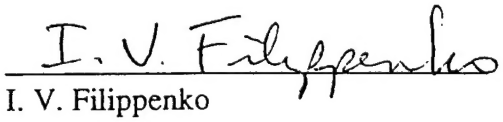
DEPARTMENT OF DEFENSE
Ft. George G. Meade, MD 20744-6000

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION IS UNLIMITED

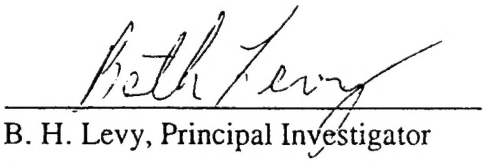
Report No.
ATR-93(3778)-2

A FORMAL DESCRIPTION OF THE INCREMENTAL TRANSLATION OF STAGE 3 VHDL INTO STATE DELTAS IN SDVS

Prepared

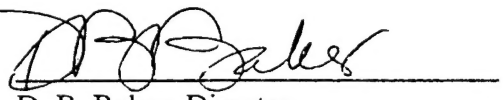


I. V. Filippenko

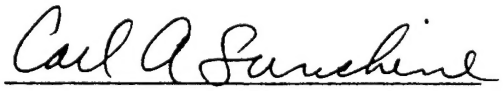


B. H. Levy, Principal Investigator
Computer Assurance Section

Approved



D. B. Baker, Director
Trusted Computer Systems Department



C. A. Sunshine, Principal Director
Computer Science and Technology Subdivision

Abstract

This report documents a formal semantic specification of Stage 3 VHDL, a subset of the VHSIC Hardware Description Language (VHDL), via translation into the temporal logic of the State Delta Verification System (SDVS). Stage 3 VHDL is the fourth of successively more sophisticated VHDL subsets to be interfaced to SDVS.

The specification is a continuation-style denotational semantics of Stage 3 VHDL in terms of *state deltas*, the distinguishing logical formulas used by SDVS to describe state transitions. The semantics is basically specified in two phases. The first phase performs static semantic analysis, including type checking and other static error checking, and collects an environment for use by the second phase. The second phase performs the actual translation of the subject Stage 3 VHDL description into state deltas. An abstract syntax tree transformation is interposed between the two translation phases.

The translator specification was, for the most part, written in DL, the semantic metalanguage of a denotational semantics specification system called DENOTE. DENOTE enables the semantic equations of the specification to be realized both as a printable representation (included in this report) and an executable Common Lisp program that constitutes the translator's implementation. However, the second phase semantics of the VHDL simulation cycle has a direct operational implementation in the VHDL translator code.

Acknowledgments

The author thanks his colleagues in the Computer Assurance Section for their support in the adaptation of SDVS to VHDL, and particularly to Tim Aiken, Jeff Cook, Beth Levy, Leo Marcus, and Dave Martin for their contributions to the formal semantic definition described in this report.

Contents

Abstract v

Acknowledgments vi

1 Introduction 1

2 History of Our Semantic Approach to VHDL 5

3 Overview of Stage 3 VHDL 7

3.1 General Remarks 7

3.2 Stage 3 VHDL Language Summary 8

4 Preliminaries 11

4.1 Environments 11

4.2 Continuations 14

4.3 Other Notation and Functions 14

5 Syntax of Stage 3 VHDL 17

5.1 Syntactic Domains 18

5.2 Syntax Equations 18

5.2.1 Concrete Syntax 18

5.2.2 Abstract Syntax: Phase 1 31

5.2.3 Abstract Syntax: Phase 2 35

6 Phase 1: Static Semantic Analysis and Environment Collection 37

6.1 Overview 37

6.2 Descriptors, Types, and Type Modes 38

6.2.1 Type and type descriptor predicates 43

6.2.2 Additional primitive accessors and predicates 45

6.3 Special-Purpose Environment Components and Functions 47

6.4 Phase 1 Semantic Domains and Functions 48

6.4.1 Phase 1 Semantic Domains 49

6.4.2 Phase 1 Semantic Functions 50
6.5 Phase 1 Semantic Equations 52
6.5.1 Stage 3 VHDL Design Files 52
6.5.2 Entity Declarations 53
6.5.3 Architecture Bodies 54
6.5.4 Port Declarations 54
6.5.5 Declarations 55
6.5.6 Concurrent Statements 72
6.5.7 Sensitivity Lists 75
6.5.8 Sequential Statements 75
6.5.9 Case Alternatives 83
6.5.10 Discrete Ranges 84
6.5.11 Waveforms and Transactions 85
6.5.12 Expressions 86
6.5.13 Primitive Semantic Equations 92

7 Interphase Abstract Syntax Tree Transformation 93
7.1 Interphase Semantic Functions 93
7.2 Transformed Abstract Syntax of Names 94
7.3 Interphase Semantic Equations 95
7.3.1 Stage 3 VHDL Design Files 95
7.3.2 Entity Declarations 95
7.3.3 Architecture Bodies 95
7.3.4 Port Declarations 95
7.3.5 Declarations 96
7.3.6 Concurrent Statements 97
7.3.7 Sensitivity Lists 98
7.3.8 Sequential Statements 98
7.3.9 Case Alternatives 99
7.3.10 Discrete Ranges 99
7.3.11 Waveforms and Transactions 100

7.3.12 Expressions 100

8 Phase 2: State Delta Generation **105**

8.1 Phase 2 Semantic Domains and Functions 105

8.1.1 Phase 2 Semantic Domains 106

8.1.2 Phase 2 Semantic Functions 107

8.2 Phase 2 Execution State 109

8.2.1 Unique Name Qualification 109

8.2.2 Universe Structure for Unique Dynamic Naming 109

8.2.3 Execution Stack 112

8.3 Special Functions 114

8.3.1 Operational Semantic Functions 114

8.3.2 Constructing State Deltas 115

8.3.3 Error Reporting 116

8.4 Phase 2 Semantic Equations 117

8.4.1 Stage 3 VHDL Design Files 117

8.4.2 Entity Declarations 122

8.4.3 Architecture Bodies 122

8.4.4 Declarations 123

8.4.5 Concurrent Statements 141

8.4.6 Sequential Statements 142

8.4.7 Waveforms and Transactions 161

8.4.8 Expressions 162

8.4.9 Expression Types 166

8.4.10 Primitive Semantic Equations 168

9 Conclusion **169**

References **171**

1 Introduction

The State Delta Verification System (SDVS), under development over the course of several years at The Aerospace Corporation, is an automated verification system that aids in writing and checking proofs that a computer program or (design of a) digital device satisfies a formal specification.

The long-term goal of the SDVS project is to create a production-quality verification system that is useful at all levels of the hierarchy of digital computer systems; our aim is to verify hardware from gate-level designs to high-level architecture, and to verify software from the microcode level to application programs written in high-level programming languages. We are currently extending the applicability of SDVS to both lower levels of hardware design and higher levels of computer programs. A technical overview of the system is provided by [1] and [2], while detailed information on the system may be found in [3] and [4].

Several features distinguish SDVS from other verification systems (refer to [5] for a detailed discussion). The underlying temporal logic of SDVS, called the *state delta logic*, has a formal model-theoretic semantics. SDVS is equipped with a theorem prover that runs in interactive or batch modes; the user supplies high-level proof commands, while many low-level proof steps are executed automatically. One of the more distinctive features of SDVS is its flexibility — there is a well-defined and relatively straightforward method of adapting the system to arbitrary application languages (to date: ISPS, Ada, and VHDL). Furthermore, descriptions in the application languages potentially serve as either specifications or implementations in the verification paradigm. Incorporation of a given application language is accomplished by translation to the state delta logic via a Common Lisp *translator* program, which is (generally) automatically derived from a formal denotational semantics for the application language.

Prior to 1987 we adapted SDVS to handle a subset of the hardware description language ISPS. However, ISPS has serious limitations regarding the specification of hardware at levels other than the register transfer level. In fiscal year 1988 we documented a study of some of the hardware verification research being conducted outside Aerospace and investigated VHDL (VHSIC Hardware Description Language), an IEEE and DoD standard hardware description language released in December 1987. We selected VHDL as a possible medium for hardware description within SDVS.

The aim of the ongoing formal hardware verification effort in SDVS is to verify hardware descriptions written in VHDL. This choice of hardware description language is particularly well-suited to our overall aim of verifying hardware designs across the spectrum from gate-level designs to high-level architectures. Indeed, the primary hardware abstraction in VHDL, the *design entity*, represents any portion of a hardware design that has well-defined inputs and outputs and performs a well-defined function. As such, "a design entity may represent an entire system, a sub-system, a board, a chip, a macro-cell, a logic gate, or any level of abstraction in between" [6].

Prerequisites for adapting SDVS to VHDL are (1) to define VHDL semantics formally in terms of SDVS's underlying logic (the state delta logic) and (2) to implement a translator from VHDL to the state delta logic. As with the incorporation of Ada into SDVS [7], the

approach taken with VHDL has been to implement increasingly complex language subsets; this has enabled a graded, structured approach to hardware verification.

In fiscal year 1989 we defined an initial subset of VHDL, called Core VHDL, that captured the most essential behavioral features of VHDL, including: `ENTITY` declarations; `ARCHITECTURE` bodies; `CONSTANT`, `VARIABLE`, `SIGNAL`, and `PORT` declarations; predefined types `BOOLEAN`, `BIT`, `BIT_VECTOR`, and `INTEGER`; variable and signal assignment statements; `IF`, `CASE`, `WAIT`, and `NULL` statements; and concurrent `PROCESS` statements. We defined both the concrete syntax and the abstract syntax for Core VHDL, formally specified its semantics and, on the basis of this semantic definition, implemented a Core-VHDL-to-state-delta translator [8].

In fiscal year 1990, SDVS was enhanced to provide the capability of verifying hardware descriptions written in Core VHDL [9, 10]. In fiscal year 1991, the translator underwent extensive revision to accommodate a second VHDL subset, Stage 1 VHDL [11], which included: `WAIT` statements in arbitrary contexts; `LOOP`, `WHILE`, and `EXIT` statements; `TRANSPORT` delay; aggregate signal assignments; and a revised translator structure.

Implemented in fiscal year 1992, Stage 2 VHDL provided a considerably more complex and capable VHDL language subset. Stage 2 VHDL extended Stage 1 VHDL with the addition of the following VHDL language features: (restricted) design files, declarative parts in entity declarations, package `STANDARD` (containing predefined types `BOOLEAN`, `BIT`, `INTEGER`, `TIME`, `CHARACTER`, `REAL`, `STRING`, and `BIT_VECTOR`), user-defined packages, `USE` clauses, array type declarations, enumeration types, subprograms (procedures and functions, excluding parameters of object class `SIGNAL`), concurrent signal assignment statements, `FOR` loops, octal and hexadecimal representations of bitstrings, default object class `SIGNAL` for ports, and general expressions of type `TIME` in `AFTER` clauses.

The VHDL language subset implemented in fiscal year 1993, Stage 3 VHDL, extends Stage 2 VHDL with the addition of subtypes of scalar types, integer type definitions, and type conversions between integer types. Furthermore, the SDVS user can now set "statement marks" (in the form of interpreted comments) for sequential statements. Finally, a facility for specifying, proving, and invoking the behavior of a VHDL subprogram — *VHDL offline characterization* — has been implemented [3]. The SDVS VHDL and Ada translators have been reengineered to a uniform implementation reflecting language similarities where these exist, and optimized for greater space- and time-efficiency.

As far as immediate plans are concerned, the scope of VHDL descriptions amenable to SDVS, as well as the specifications that could be proved about them, will be significantly broadened by (1) enhancing the SDVS Simplifier with support for reasoning about symbolic representations of VHDL time, and (2) augmenting the SDVS proof language with a command for induction over VHDL simulation cycles (or adapting the existing **induct** command for that purpose).

The purpose of the present report is to provide a formal description of the translation of Stage 3 VHDL hardware descriptions into state deltas. This amounts to a formal semantic specification of Stage 3 VHDL, presented herein as a continuation-style denotational semantics [12] for which the state delta language provides the semantic domain. The translation basically consists of parsing followed by two semantic analysis phases.

The first phase receives the abstract syntax tree generated by the Stage 3 VHDL parser for a given hardware description, and:

- performs static semantic analysis, including type checking;
- collects an environment that associates all names declared in the subject Stage 3 VHDL hardware description with their attributes;
- appropriately disambiguates identical names declared in different scopes, as required by the static block structure of the hardware description; and
- for the convenience of the second phase, transforms the abstract syntax tree of the subject hardware description.

Phase 2 receives the transformed abstract syntax tree and the environment constructed by Phase 1, and uses these to translate the Stage 3 VHDL hardware description into state deltas. This translation is incremental, in the sense that it is driven by symbolic execution of the hardware description, producing further state deltas as symbolic execution proceeds.

The Stage 3 VHDL formal description is an extensive revision and expansion of the formal specifications of the Core VHDL, Stage 1 VHDL, and Stage 2 VHDL translators [8, 11, 13]. The Stage 3 VHDL translator specification was written in DL, the semantic metalanguage of a denotational semantics specification system called DENOTE [14]. DENOTE enables the semantic equations of the specification to be *automatically* translated into both a printable representation (included in this report) and an executable Common Lisp program that constitutes the translator's implementation.

This report is organized as follows.

- Our approach to the semantics of Stage 3 VHDL is discussed in Section 2.
- Section 3 contains an overview of the Stage 3 VHDL subset.
- Section 4 provides preliminary information (background and notation) on the particular method of semantic description used.
- Section 5 lists both the concrete and abstract syntax of Stage 3 VHDL.
- Section 6 presents the Stage 3 VHDL static semantics.
- Section 7 presents the interphase abstract syntax tree transformation.
- Section 8 presents the Stage 3 VHDL dynamic semantics in terms of state deltas.
- Finally, some concluding remarks are made in Section 9.

2 History of Our Semantic Approach to VHDL

The VHDL translator essentially functions as a simulator kernel, maintaining a clock and a list of future events that are defined as state deltas. For Core VHDL (fiscal years 1989 and 1990), the translator transformed possibly multiple Core VHDL statements: sequential statements between `WAIT` statements within a process were all translated and then *composed* into a single state delta. The translator updated the clock to the next time at which a signal driver became active or a process resumed. As the clock advanced, the translator *merged* the composite state deltas into a single state delta that specified the behavior of all processes at that point in the execution.

For Stage 1 VHDL (fiscal year 1991), we re-evaluated the feasibility of using composition in the translation of VHDL to state deltas, and concluded that although composition had initially seemed viable in the case of Core VHDL, it is *impossible in principle* to apply the technique to more complex VHDL subsets, as the attempt would require the ability to compose over sections of VHDL code that would necessitate static proof in SDVS. More generally, the ability to compose over arbitrary `WAIT`-bracketed code in `PROCESS` statements would be tantamount to the automatic construction of correctness proofs without user intervention — a theoretically undecidable problem.

Therefore, we abandoned composition for Stage 1 VHDL and subsequent SDVS VHDL subsets. Instead, within a given execution (simulation) cycle, processes are translated sequentially, in the order in which they appear in the VHDL description, and the user has control over stepping through the sequential statements within each process. Thus, rather than trying to have the VHDL translator model the concurrency of the processes, we choose to take for granted a certain "metatheorem" about VHDL: that any two sequentializations of the processes are equivalent. A brief justification for this point of view is that the problem of mutual exclusion is not a concern in VHDL, since

- all variables are local to the process in which they are declared, and
- distinct processes modify distinct drivers of a given signal (known as a *resolved signal*), and the ultimate signal value is obtained by application of a user-defined *resolution function*.[1]

A gratifying benefit of the revised translation strategy is that the understandability of the resulting proofs has been remarkably improved — the dynamic flow of process execution precisely reflects the simulation semantics of VHDL (as defined in the *VHDL Language Reference Manual* [6]), but with the crucial aspect of symbolic execution (use of abstract values rather than concrete) thrown in. The current Stage 3 VHDL translator thus functions as a "symbolic simulator," with the effect of being reasonably intuitive as a proof engine.

[1] As of Stage 3 VHDL, however, *resolved signals* are still disallowed.

3 Overview of Stage 3 VHDL

Stage 3 VHDL comprises a relatively powerful *behavioral* subset of VHDL. That is to say, Stage 3 VHDL descriptions are confined to the specification of hardware behavior or data flow, rather than structure. More comprehensive VHDL subsets for SDVS will include constructs for the structural description of hardware in terms of its hierarchical decomposition into connected subcomponents; this enhancement may be implemented in Stage 4 VHDL.

3.1 General Remarks

The primary VHDL abstraction for modeling a digital device is the *design entity*. A design entity consists of two parts: an *entity declaration*, providing an external view of the component by declaring the input and output *ports*, and an *architecture body*, giving an internal view in terms of component behavior or structure.

In Stage 3 VHDL, each architecture body is constrained to be *behavioral*, consisting of a set of *declarations* and *concurrent statements* defining the functional interpretation of the device being modeled. The allowable concurrent statements are of two kinds: `PROCESS` statements and *concurrent signal assignment* statements, to be discussed below.

A `PROCESS` statement, the most fundamental kind of behavioral concurrent statement in VHDL, is a block of sequential *zero-time statements* that execute sequentially but "instantaneously" in *zero time* [15], and some (possibly none) distinguished sequential `WAIT` statements whose purpose is to suspend process execution and allow time to elapse.

A process typically schedules future values to appear on data holders called *signals*, by means of *sequential signal assignment* statements. The execution of a signal assignment statement does not immediately update the value of the *target signal* (the signal assigned to); rather, it updates the target signal's associated *driver* signal by placing (at least one) new *transaction*, or time-value pair, on the *waveform* that is the list of such transactions contained in the driver. Each transaction projects that the signal will assume the indicated value at the indicated time; the time is computed as the sum of the current clock time of the model and the delay specified (explicitly or implicitly) by the signal assignment statement.

Two types of time delay can be specified by a sequential signal assignment statement, and Stage 3 VHDL encompasses both. *Inertial delay*, the default, models a target signal's inertia that must be overcome in order for the signal to change value; that is, the scheduled new value must persist for at least the time period specified by the delay in order actually to be attained by the target signal. *Transport delay*, on the other hand, must be explicitly indicated in the signal assignment statement with the reserved word `TRANSPORT`, and models a "wire delay" wherein any pulse of whatever duration is propagated to the target signal after the specified delay.

In lieu of explicit `WAIT`s, a process may have a *sensitivity list* of signals that activate process resumption upon receiving a distinct new value (an *event*). The sensitivity list implicitly inserts a `WAIT` statement as the last statement of the process body.

The other class of concurrent statement in Stage 3 VHDL is that of *concurrent signal assignment* statements. These always represent equivalent PROCESS statements, and come in two varieties: *conditional signal assignment* and *selected signal assignment*. A conditional signal assignment is equivalent to a process with an embedded IF statement whose branches are sequential signal assignments; similarly, a selected signal assignment is equivalent to a process with an embedded (possibly degenerate) CASE statement whose branches are sequential signal assignments. The VHDL translator syntactically transforms concurrent signal assignment statements to their corresponding PROCESS statements prior to translation into state deltas.

Signals act as data pathways between processes. Each process applies operations to values being passed through the design entity. We may regard a process as a program implementing an algorithm, and a Stage 3 VHDL description as a collection of independent programs running in parallel.

In full VHDL, a target signal can be assigned to in multiple processes, with a separate driver for updating by each process; the value taken on by the signal at any particular time is then computed by a user-defined *resolution function* of these drivers. As did previous SDVS VHDL subsets, Stage 3 VHDL disallows such *resolved signals*: a signal is not permitted to appear as the target of a sequential signal assignment statement in more than one process body; equivalently, every signal has a unique driver. Resolved signals and their resolution functions will be implemented in a future version of SDVS.

The Stage 3 VHDL data types are: BOOLEAN, BIT, UNIVERSAL_INTEGER, INTEGER, REAL (preliminary version), TIME (a predefined *physical type* of INTEGER range), CHARACTER, STRING (arrays of characters), BIT_VECTOR (arrays of bits), user-defined *enumeration types*, user-defined *array types*, *subtypes* of scalar types, and *integer type definitions*. Furthermore, explicit *type conversions* between integer types are allowed. The preliminary implementation allows VHDL descriptions involving type REAL to be parsed and translated, but provides no support for reasoning about floating point numbers.

3.2 Stage 3 VHDL Language Summary

Concrete and abstract syntaxes for Stage 3 VHDL have been defined — see Section 5 — as required, of course, for the implementation of the Stage 3 VHDL translator. The following is a convenient synopsis of the Stage 3 VHDL language subset.

- VHDL design files
  - entity declarations, architecture bodies
  - *restriction*: unique entity and architecture per file
- package STANDARD
  - predefined types:
    BOOLEAN, BIT, UNIVERSAL_INTEGER, INTEGER, TIME, CHARACTER, REAL, STRING, BIT_VECTOR
  - various units of type TIME: FS, PS, NS, US, MS, SEC, MIN, HR

  - *restriction*: the implementation of type `REAL` is preliminary

- user-defined packages
  - package declarations
  - package bodies
- `USE` clauses for accessing packages
  - *restriction*: packages must be used in their entirety
- entity declarations
  - entity header: port declarations
  - entity declarative part: other declarations
- architecture bodies
- object declarations
  - `CONSTANT`, `VARIABLE`, `SIGNAL`
  - octal and hexadecimal representations of bitstrings
  - default object class `SIGNAL` for entity ports
- array type declarations
  - arrays of arbitrary element type
  - bidirectional arrays, unconstrained arrays
- user-defined enumeration types
- subtypes of scalar types
- integer type definitions
- type conversion
- signals of arbitrary types
- subprograms
  - procedures and functions: declarations and bodies
  - *restriction*: excluding parameters of object class `SIGNAL`
- concurrent statements
  - `PROCESS` statements
  - conditional signal assignments
  - selected signal assignments
- sequential statements

- null statement: `NULL`
- variable assignments (scalar & composite)
- signal assignments (scalar & composite, inertial or `TRANSPORT` delay)
- conditionals: `IF`, `CASE`
- loops: `LOOP`, `WHILE`, `FOR`
- loop exits: `EXIT`
- subprogram calls
- subprogram return: `RETURN`
- process suspension: `WAIT`

- operators
  - numeric unary operators: `ABS`, `+`, `-`
  - numeric binary operators: `+`, `-`, `*`, `/`, `**` (exponentiation), `MOD` (modulus), `REM` (remainder)
  - boolean and bit operators: `NOT`, `AND`, `NAND`, `OR`, `NOR`, `XOR`
  - relational operators: `=`, `/=`, `<`, `<=`, `>`, and `>=`
  - array concatenation operator: `&`
  - *restriction*: `=`, `/=`, and `&` are the only Stage 3 VHDL operators defined for composite types (i.e., `BIT_VECTOR` and user-defined array types).

4 Preliminaries

The purpose of this section is to provide some of the background and notation necessary for the research documented in this report. It is assumed that the reader is familiar with

- the descriptive aspects of the denotational technique for expressing the semantics of programming languages (including concepts such as syntax, semantic functions, lambda notation, curried function notation, environments, and continuations) as presented in [12]; and
- the theory and practice of state deltas [3, 16, 17].

Denotational semantic definitions of programming languages consist of two parts: syntax and semantics. The syntax part consists of domain equations (equivalent to productions of a context-free grammar) that define the syntactic variables (analogous to grammar nonterminals) and the (abstract) syntactic elements of the language. The semantic part defines a semantic function for each syntactic variable and the definition (by syntactic cases) of these functions; it also defines auxiliary functions that are used in the definition of the semantic functions. The semantic functions constitute a syntax-directed mapping from the syntactic constructs of the language to their corresponding semantics.

Certain principal notions, among which are *environments* and *continuations*, are central to standard denotational semantic definitions of programming languages.

4.1 Environments

Environments are functions from identifiers to their "definitions"; these definitions are called *denotable values*. Identifiers that have no corresponding definition are formally bound to the special token ***UNBOUND***. The identifiers are names for objects (e.g. constants, variables, procedures, and exceptions) in a program written in the language being defined. Environments are usually created and modified by the elaboration of declarations in the language.

The domain of environments, **Env**, is typically

$$\mathbf{Env} = \mathbf{Id} \rightarrow (\mathbf{Dv} + \mathbf{*UNBOUND*})$$

where **Id** and **Dv** are, respectively, the domains of identifiers and denotable values. If **r** is an environment, then **r(id)** is the value (***UNBOUND*** or a **Dv**-value) bound to the identifier **id**. The *empty environment* **r0** is the environment in which **r0(id)** = ***UNBOUND*** for every identifier **id**. In definitions of languages that have block-structured scoping, it is necessary to combine two environments that may each associate a denotable value with the same identifier. If **r1** and **r2** are environments, then **r1[r2]** is a combined environment defined by

$$\mathbf{r1[r2](id)} = (\mathbf{r2(id)} = \mathbf{*UNBOUND*} \rightarrow \mathbf{r1(id)}, \mathbf{r2(id)})$$

where (a → b,c) is an abbreviation for **if** a **then** b **else** c. That is, in **r1[r2]**, the **r2**-value of an identifier "overrides" the **r1**-value of that same identifier, except when its **r2**-value is

UNBOUND. An environment can be changed by this means. If **r** is an environment, **d** a value, and **id** an identifier, then **r[d/id]** denotes an environment that is the same as **r** except that **(r[d/id])(id) = d**.

Tree-Structured Environments

When the use of the above combination of environments is inconvenient or inappropriate, it is sometimes necessary to use a structured collection of environments. A *tree-structured environment* (TSE) is a tree whose nodes are environments and whose edges are labeled by identifiers or numerals, called *edge labels*, where no two edges emanating from a given node can have the same label. A *path* is a list of zero or more edge labels. Such a path denotes a sequence of connected edges from the root node to another node of a tree-structured environment. A path **p** can be *extended* by an edge labeled **elbl** via **%(p)(elbl)**, where

%(path)(id) = append(path,(id))

Formally, a TSE can be regarded as a partial function from paths to environments. Thus the *set of paths* in a TSE **t** is precisely the set of paths **p** for which **t(p)** is defined. If **t** is a TSE and **p** is a path in **t**, then **t(p)** denotes the unique environment in **t** located at the end of **p**.

If **t** is a TSE and **p** is one of its paths, the pair **(t,p)** can be used to represent the set of environments containing all of the identifier bindings visible at a given point in a Stage 3 VHDL hardware description, where the identifiers in **p** are the names of the lexical scopes whose local environments are on the path **p**. At the program point whose identifier bindings are represented by **(t, (elbl$_1$, ..., elbl$_n$))**, **t((elbl$_1$, ..., elbl$_n$))** is the most *local* set of bindings, ..., and **t(ϵ)** is the most *global* set of bindings, where ϵ denotes the empty path. Thus **t(p)(id)** is the value bound to **id** in the most local environment of **(t,p)**.

Qualified Names

The same identifier is bound in *every* component environment of a TSE, although many (if not most) of those bindings may be to ***UNBOUND***. It is convenient to be able to distinguish uniquely an occurrence of an identifier by prefixing to the identifier a representation of the path that designates the location in the TSE of the environment associated with that instance. Such a uniquely distinguished identifier will be called a *fully qualified name*. Thus if **t** is a TSE, **p** one of its paths, and **id** an identifier, then **$(p)(id)** is **id**'s fully qualified name relative to **t(p)**. If **p = (elbl$_1$, ..., elbl$_n$)**, then **$(p)(id)** is represented as **elbl$_1$.elbl$_2$. ... .elbl$_n$.id**. When **p** = ϵ (empty path), **$($\epsilon$)(id)** is simply represented by **id**. **$** is defined by

$(path)(id) = (path = ϵ $\rightarrow$ id, $(rest(path))(catenate(last(path),".",id)))

The function **rest** returns a list consisting of the first $n-1$ elements of an n-element list, and **catenate** is a curried function that concatenates its (variable number of) arguments into an atom.

Identifiers qualified with the full TSE path that locates their associated component environment are cumbersome and hard to read. If only those instances of identifiers *not* bound to ***UNBOUND*** are of interest, then such full name qualification may be unnecessary.

Often a *suffix* of this path is sufficient to distinguish uniquely an instance of such an identifier. An identifier so qualified is said to be *uniquely qualified.* In the limit, if *all* identifiers not bound to ***UNBOUND*** were distinct, then no qualification (an empty suffix) would be necessary to distinguish them. Given a TSE, it is possible to determine the minimum path suffix necessary to distinguish uniquely each identifier instance; this is done in our implementation of Stage 3 VHDL.

Descriptors

The denotable values to which identifiers are bound in the component environments of a TSE are called *descriptors.*

A descriptor contains several fields of information, each of which holds an *attribute* of the identifier instance to which the descriptor is bound in a given TSE component environment. The number of fields in a descriptor depends on the attributes of its associated identifier, but each descriptor always has fields that contain the identifier to which it is bound, the identifier instance's *statically uniquely qualified name* (see Section 8.2.1), and a tag that identifies the kind of descriptor (and hence its remaining fields).

Descriptors for Stage 3 VHDL are discussed in detail in Section 6.2.

Tree-Structured Environment Access

Certain non-***UNBOUND*** (i.e., denotable) values of an identifier **id** in **(t,p)** can be accessed by the functions **lookup** and **lookup-local**. These functions are given later in the context of semantic equations in which they are used.

Tree-Structured Environment Modification

A TSE's component environments can be modified (in particular, descriptors can be bound to unbound identifiers or existing descriptors can be modified) via a function built into DENOTE. This function, **enter**, is used extensively in the DENOTE description of the Stage 3 VHDL translator. **enter(t)(p)(id)(d)**, where **t** is a TSE, **p** a path in **t**, **id** an identifier, and **d** a *partial* descriptor (containing all its fields except the identifier field), yields a TSE that is the same as **t** except that its component environment **t(p)** is replaced by the environment

t(p)[d'/id], where if **d** = ⟨**qid**, **tag**, ... ⟩, then **d'** = ⟨**id**, **qid**, **tag**, ... ⟩.

Tree-Structured Environment Extension

One can add additional component environments to a TSE by *extending* it. If **t** is a TSE, **p** a path in **t**, and **elbl** an edge label, and if **%(p)(elbl)** is *not* a path in **t**, then

extend(t)(p)(elbl)

denotes the TSE that is the same as **t** except that

(extend(t)(p)(elbl))(%(p)(elbl)) = r0.

Thus one can extend **t** along one of its paths **p** by adding a legally labeled edge onto the end of **p** and placing a node that is the empty environment **r0** at the end of that extended path **%(p)(elbl)**.

4.2 Continuations

Continuations are a technical device for capturing the semantics of transfers of control, whether they be explicit (**gotos**, returns from procedures and functions) or implicit (normal sequential flow of control to the next program element, abnormal termination of program execution). Continuations are functions intended to map the "normal" result of a semantic function to some ultimate "final answer" [some final value(s) or an error message]. If the semantic function does not produce a normal result, its continuation can be ignored and some "abnormal" final answer (such as an error message) can be produced instead.

For example, in the first phase of our formal description of the Stage 3 VHDL translator, a continuation supplied to a semantic function that elaborates declarations normally maps a new "translation state" to a final answer, but if a declaration illegally duplicates or conflicts with an existing definition, then the continuation is ignored and an error message (such as DUPLICATE-DECLARATION) is the resulting final answer.

The initiation of the second phase of our formal description of the Stage 3 VHDL translator assumes that the program has first "passed" the first phase without error. In fact, the second phase is used as the continuation for the first.

4.3 Other Notation and Functions

Fairly standard lambda notation (see [12]) is used in this report, except that structured arguments are permitted in lambda-abstractions. Lambda-abstractions normally have the form λ**x.body**, where **body** is a lambda-term and **x** may be free in **body**. The term λ**x.**λ**y.body** is printed as λ**x,y.body**. If **x** is, for example, a *pair*, then the components of **x** can be represented in **body** by the application of projection functions to **x**. Instead, the individual components of **x** can be bound to variables **y** and **z** that appear free in **body** (instead of projection functions applied to **x**) by using the abstraction λ**(y,z).body** . This is defined if and only if the value of **x** is indeed a pair. This notation will be used only when its result is defined.

A list is represented in the usual way: **(x,y,z)**. Standard Lisp functions are used, but they are curried, as in **cons(x)(y)** and **append(x)(y)**. If **x** is a *nonempty* sequence (list), then **hd(x)** denotes its first element and **tl(x)** the sequence (list) of its remaining components; **x = cons(hd(x))(tl(x))**.

Some general-purpose functions are **second**, **third**, **fourth**, **fifth**, **sixth**, and **last**, which return the second, third, fourth, fifth, sixth, and last elements, respectively, of a list. Additionally, we have **rest**, which returns a list consisting of the first $n - 1$ elements of an n-element list, and **length**, which returns the integer length of a list.

second(x) = hd(tl(x))

third(x) = hd(tl(tl(x)))

fourth(x) = hd(tl(tl(tl(x))))

fifth(x) = hd(tl(tl(tl(tl(x)))))

$\text{sixth}(x) = \text{hd}(\text{tl}(\text{tl}(\text{tl}(\text{tl}(\text{tl}(x))))))$

$\text{last}(\text{id}^+) = (\text{null}(\text{tl}(\text{id}^+)) \rightarrow \text{hd}(\text{id}^+), \text{last}(\text{tl}(\text{id}^+)))$

$\text{rest}(\text{id}^+) = (\text{null}(\text{tl}(\text{id}^+)) \rightarrow \epsilon, \text{cons}(\text{hd}(\text{id}^+), \text{rest}(\text{tl}(\text{id}^+))))$

$\text{length}(x) = (\text{null}(x) \rightarrow 0, 1 + \text{length}(\text{tl}(x)))$

5 Syntax of Stage 3 VHDL

Three Stage 3 VHDL syntaxes are used by the translator: a *concrete syntax*, which is SLR(1) and is used for parsing Stage 3 VHDL hardware descriptions; and two *abstract syntaxes*, which are used, respectively, in Phases 1 and 2 of the semantic definition. The concrete syntax is intended to be the "reference" grammar for the Stage 3 VHDL language subset.

In all three syntaxes the syntactic constructs are the members of *syntactic domains*, which are of two kinds: *primitive* and *compound*. The primitive syntactic domains are given. The compound syntactic domains are functions of the primitive domains; these functional dependencies are expressed as a set of *syntax equations* represented as productions of a context-free grammar. Terminals and nonterminals of this grammar range, respectively, over the primitive and compound syntactic domains. Only those syntactic domains of the abstract syntax that actually appear in a semantic equation will be given explicit names; other syntactic domains will be unnamed, as these names are not used in the specification.

The terminal classes are: identifiers, unsigned decimal numerals, bit literals, character literals, bitstrings (binary, octal, and hexadecimal), and strings. The remaining terminal symbols serve as reserved words.

The concrete syntax of Stage 3 VHDL, being SLR(1), is unambiguous. The abstract syntaxes are considerably smaller than the concrete syntax, because they are not concerned with providing a parsable representation of Stage 3 VHDL, but rather simply provide the minimum syntactic information necessary for a syntax-directed semantic specification. Their use yields a more compact formal definition.

The translation of a hardware description (from concrete syntax) to its abstract syntax representation is accomplished by semantic action routines in the Stage 3 VHDL parser. This process is straightforward, and a formal specification of how the Phase 1 abstract syntax is derived from the concrete syntax is omitted from this report. It is felt that the correspondence between the concrete and Phase 1 syntaxes is so close that no such formal specification is needed. The derivation of Phase 2 syntactic objects from corresponding Phase 1 syntactic objects is explicit in the specification of the interphase abstract syntax tree transformation; see Section 7.

There are some minor variations between the concrete and abstract syntaxes of Stage 3 VHDL. For example, in the concrete syntax, labels for `PROCESS` statements and loops (`LOOP`, `WHILE`, `FOR` statements) are optional. It was found, however, that the semantics of Stage 3 VHDL requires that every process and loop have a label. Thus in the abstract syntaxes (which drive the semantics), process and loop labels are *required*. This is enforced by having the parser and the constructor of the Phase 1 abstract syntax tree supply a distinct system-generated label for each unnamed process and loop. These labels are taken from a primitive syntactic domain **SysId** of *system-generated identifiers*, disjoint from the primitive syntactic domain **Id** of identifiers. Similarly, anonymous array types are given distinct system-generated names.

The following subsections present the syntactic domains and equations for Stage 3 VHDL.

5.1 Syntactic Domains

Primitive Syntactic Domains

`id` : **Id**	identifiers
SysId	system-generated identifiers (disjoint from **Id**)
`bit` : **BitLit**	bit literals
`constant` : **NumLit**	numeric literals (unsigned decimal numerals)
`char` : **CharLit**	character literals
`bitstring`, `octstring`, `hexstring` : **BitStr**	bitstring literals
`string` : **Str**	string literals

Compound Syntactic Domains

`design-file` : **Design**	design files
`ent-decl` : **Ent**	entity specifications
`arch-body` : **Arch**	architecture body specifications
`port-decl` : **PDec**	port declarations
`decl`, `pkg-decl`, `pkg-body`, `use-clause` : **Dec**	declarations
`con-stat` : **CStat**	concurrent statements
`seq-stat` : **SStat**	sequential statements
`case-alt` : **Alt**	case alternatives
`discrete-range` : **Drg**	discrete ranges
`waveform` : **Wave**	waveforms
`transaction` : **Trans**	transactions
`expr` : **Expr**	expressions
`ref` : **Ref**	references
`unary-op` : **Uop**	unary operators
`binary-op` : **Bop**	binary operators
`relational-op` : **Bop**	relational operators

5.2 Syntax Equations

In Sections 5.2.1, 5.2.2, and 5.2.3 we present, respectively, the concrete syntax for Stage 3 VHDL hardware descriptions admissible as input to the SDVS VHDL language parser, the syntax of VHDL abstract parse trees generated by the parser for use by Phase 1 of the VHDL translator, and the syntax of transformed parse trees produced during Phase 1 for use by translator Phase 2.

5.2.1 Concrete Syntax

The concrete syntax for Stage 3 VHDL is shown below.

The productions are numbered for reference purposes. The first production and the nonterminal `**start**` are inserted by the SLR(1) grammar analyzer to facilitate SLR(1) parsing,

and the (terminal) symbol *E* denotes the beginning or end of a file. Terminal symbols appear in uppercase letters, while nonterminal symbols and pseudo-terminals (terminals denoting a set of values) are in lowercase; pseudo-terminals are prefixed by a "dot" (.).

STAGE 3 VHDL CONCRETE SYNTAX

```
1  **start**
      ::= *E* design-file *E*

2  design-file
      ::= DESIGN_FILE .id IS init pkg-decl-list pkg-body-list
          use-clause-list entity-declaration architecture-body

3  init
      ::=

4  pkg-decl-list
      ::=
5       | pkg-decl-list pkg-decl

6  pkg-decl
      ::= PACKAGE .id IS pkg-decl-part END opt-id ;

7  pkg-decl-part
      ::= pkg-decl-item-list

8  pkg-decl-item-list
      ::=
9       | pkg-decl-item-list pkg-decl-item

10 pkg-decl-item
      ::= const-decl
11      | sig-decl
12      | type-decl
13      | subtype-decl
14      | subprog-decl
15      | use-clause

16 opt-id
      ::=
17      | .id

18 pkg-body-list
      ::=
19      | pkg-body pkg-body-list

20 pkg-body
      ::= PACKAGE BODY .id IS pkg-body-decl-part END opt-id ;

21 pkg-body-decl-part
      ::= pkg-body-decl-item-list

22 pkg-body-decl-item-list
      ::=
23      | pkg-body-decl-item-list pkg-body-decl-item
```

```
24  pkg-body-decl-item
       ::=  const-decl
25        |  type-decl
26        |  subtype-decl
27        |  subprog-decl
28        |  subprog-body
29        |  use-clause

30  use-clause-list
       ::=
31        |  use-clause-list  use-clause

32  use-clause
       ::=  USE  dotted-name-list  ;

33  dotted-name-list
       ::=  dotted-name
34        |  dotted-name-list  ,  dotted-name

35  dotted-name
       ::=  .id
36        |  dotted-name  .  .id

37  entity-declaration
       ::=  ENTITY  .id  IS  ent-header  END  opt-id  ;
38        |  ENTITY  .id  IS  ent-header  ent-decl-part  END  opt-id  ;

39  ent-header
       ::=  opt-port-clause

40  opt-port-clause
       ::=
41        |  port-clause

42  ent-decl-part
       ::=  ent-decl-item-list

43  ent-decl-item-list
       ::=  ent-decl-item
44        |  ent-decl-item-list  ent-decl-item

45  ent-decl-item
       ::=  const-decl
46        |  sig-decl
47        |  type-decl
48        |  subtype-decl
49        |  subprog-decl
50        |  subprog-body
51        |  use-clause

52  architecture-body
       ::=  ARCHITECTURE  .id  OF  .id  IS  arch-decl-part  BEGIN
            arch-stat-part  END  opt-id  ;

53  arch-decl-part
       ::=  arch-decl-item-list
```

```
54  arch-decl-item-list
        ::=
55        | arch-decl-item-list  arch-decl-item

56  arch-decl-item
        ::=  const-decl
57        | sig-decl
58        | type-decl
59        | subtype-decl
60        | subprog-decl
61        | subprog-body
62        | use-clause

63  arch-stat-part
        ::=  con-stats

64  port-clause
        ::=  PORT  (  port-list  )  ;

65  port-list
        ::=  interface-list

66  interface-list
        ::=  interface-sig-decl
67        | interface-list  ;  interface-sig-decl

68  interface-sig-decl
        ::=  opt-signal  id-list  :  opt-mode  type-mark  opt-init
69        | opt-signal  id-list  :  opt-mode  slice-name  opt-init

70  opt-signal
        ::=
71        | SIGNAL

72  id-list
        ::=  .id
73        | id-list  ,  .id

74  opt-mode
        ::=
75        | mode

76  mode
        ::=  IN
77        | OUT
78        | INOUT
79        | BUFFER

80  type-mark
        ::=  dotted-name

81  slice-name
        ::=  type-mark  (  discrete-range  )

82  discrete-range
        ::=  range
```

```
 83  range
        ::=  simple-expr  direction  simple-expr

 84  direction
        ::=  TO
 85       |  DOWNTO

 86  opt-init
        ::=
 87       |  :=  expr

 88  const-decl
        ::=  CONSTANT  id-list  :  type-mark  :=  expr  ;
 89       |  CONSTANT  id-list  :  slice-name  :=  expr  ;

 90  var-decl
        ::=  VARIABLE  id-list  :  type-mark  opt-init  ;
 91       |  VARIABLE  id-list  :  slice-name  opt-init  ;

 92  sig-decl
        ::=  SIGNAL  id-list  :  type-mark  opt-init  ;
 93       |  SIGNAL  id-list  :  slice-name  opt-init  ;

 94  type-decl
        ::=  enum-type-decl
 95       |  array-type-decl
 96       |  integer-type-decl

 97  enum-type-decl
        ::=  TYPE  .id  IS  enum-type-def  ;

 98  enum-type-def
        ::=  (  id-list  )
 99       |  (  char-list  )

100  char-list
        ::=  character-literal
101       |  char-list  ,  character-literal

102  array-type-decl
        ::=  TYPE  .id  IS  array-type-def  ;

103  array-type-def
        ::=  ARRAY  (  discrete-range  )  OF  type-mark

104  integer-type-decl
        ::=  TYPE  .id  IS  RANGE  discrete-range  ;

105  subtype-decl
        ::=  SUBTYPE  .id  IS  type-mark  opt-constraint  ;

106  opt-constraint
        ::=
107       |  constraint

108  constraint
```

```
       ::= range-constraint

109 range-constraint
       ::= RANGE discrete-range

110 subprog-decl
       ::= subprog-spec ;

111 subprog-spec
       ::= PROCEDURE .id opt-procedure-formal-part
112      | FUNCTION .id opt-function-formal-part RETURN type-mark

113 opt-procedure-formal-part
       ::=
114      | ( procedure-par-spec-list )

115 opt-function-formal-part
       ::=
116      | ( function-par-spec-list )

117 procedure-par-spec-list
       ::= procedure-par-spec
118      | procedure-par-spec-list ; procedure-par-spec

119 function-par-spec-list
       ::= function-par-spec
120      | function-par-spec-list ; function-par-spec

121 procedure-par-spec
       ::= proc-object-class id-list : procedure-par-mode
           type-mark opt-expr
122      | id-list : IN type-mark opt-expr
123      | id-list : OUT type-mark opt-expr
124      | id-list : INOUT type-mark opt-expr

125 function-par-spec
       ::= fn-object-class id-list : function-par-mode type-mark
           opt-expr

126 proc-object-class
       ::= CONSTANT
127      | VARIABLE

128 fn-object-class
       ::=
129      | CONSTANT

130 procedure-par-mode
       ::=
131      | IN
132      | OUT
133      | INOUT

134 function-par-mode
       ::=
135      | IN
```

```
136  subprog-body
        ::= subprog-spec IS subprog-decl-part BEGIN
            subprog-stat-part END opt-id ;

137  subprog-decl-part
        ::= subprog-decl-item-list

138  subprog-decl-item-list
        ::=
139       | subprog-decl-item-list subprog-decl-item

140  subprog-decl-item
        ::= const-decl
141       | var-decl
142       | type-decl
143       | subtype-decl
144       | subprog-decl
145       | subprog-body
146       | use-clause

147  subprog-stat-part
        ::= seq-stats

148  con-stats
        ::=
149       | con-stats con-stat

150  con-stat
        ::= process-stat
151       | concurrent-sig-assn-stat

152  process-stat
        ::= opt-unit-label PROCESS process-decl-part BEGIN
            process-stat-part END PROCESS opt-id ;
153       | opt-unit-label PROCESS ( sensitivity-list )
            process-decl-part BEGIN process-stat-part END PROCESS
            opt-id ;

154  opt-unit-label
        ::=
155       | .id :

156  process-decl-part
        ::= process-decl-item-list

157  process-decl-item-list
        ::=
158       | process-decl-item-list process-decl-item

159  process-decl-item
        ::= const-decl
160       | var-decl
161       | type-decl
162       | subtype-decl
163       | subprog-decl
164       | subprog-body
165       | use-clause
```

```
166  process-stat-part
        ::=  seq-stats

167  concurrent-sig-assn-stat
        ::=  selected-sig-assn-stat
168       |  conditional-sig-assn-stat

169  selected-sig-assn-stat
        ::=  opt-unit-label  WITH  expr  SELECT
             target  <=  opt-transport  selected-waveforms  ;
170       |  .atmark
             opt-unit-label  WITH  expr  SELECT
             target  <=  opt-transport  selected-waveforms  ;

171  opt-transport
        ::=
172       |  TRANSPORT

173  selected-waveforms
        ::=  selected-waveform
174       |  selected-waveforms  ,  selected-waveform

175  selected-waveform
        ::=  waveform  WHEN  choices

176  conditional-sig-assn-stat
        ::=  target  <=  opt-transport  conditional-waveforms  waveform ;
177       |  .atmark
             target  <=  opt-transport  conditional-waveforms waveform  ;
178       |  .id  :  target  <=  opt-transport  conditional-waveforms waveform  ;
179       |  .atmark
             .id  :  target  <=  opt-transport conditional-waveforms  waveform  ;

180  conditional-waveforms
        ::=
181       |  conditional-waveforms  conditional-waveform

182  conditional-waveform
        ::=  waveform  WHEN  expr  ELSE

183  waveform
        ::=  waveform-elt-list

184  waveform-elt-list
        ::=  waveform-elt
185       |  waveform-elt-list  ,  waveform-elt

186  waveform-elt
        ::=  expr
187       |  expr  AFTER  expr

188  seq-stats
        ::=
189       |  seq-stats  seq-stat

190  seq-stat
```

```
        ::= null-stat
191       | var-assn-stat
192       | sig-assn-stat
193       | if-stat
194       | case-stat
195       | loop-stat
196       | exit-stat
197       | return-stat
198       | proc-call-stat
199       | wait-stat

200   null-stat
        ::= NULL ;
201       | .atmark NULL

202   var-assn-stat
        ::= name := expr ;
203       | .atmark name := expr ;

204   sig-assn-stat
        ::= target <= opt-transport waveform ;
205       | .atmark target <= opt-transport waveform ;

206   if-stat
        ::= if-head if-tail
207       | .atmark if-head if-tail

208   if-head
        ::= IF expr THEN seq-stats
209       | if-head ELSIF expr THEN seq-stats

210   if-tail
        ::= END IF ;
211       | ELSE seq-stats END IF ;

212   case-stat
        ::= CASE expr IS case-alt-list END CASE ;
213       | .atmark CASE expr IS case-alt-list END CASE ;

214   case-alt-list
        ::= case-alt
215       | case-other-alt
216       | case-alt case-alt-list

217   case-alt
        ::= WHEN choices => seq-stats

218   case-other-alt
        ::= WHEN OTHERS => seq-stats

219   choices
        ::= choice
220       | choices | choice

221   choice
        ::= simple-expr
222       | discrete-range
```

```
223  loop-stat
        ::=  simple-loop
224       |  while-loop
225       |  for-loop

226  simple-loop
        ::=  opt-unit-label  LOOP  seq-stats  END  LOOP  opt-id  ;
227       |  .atmark  opt-unit-label  LOOP  seq-stats  END  LOOP
             opt-id  ;

228  while-loop
        ::=  opt-unit-label  WHILE  expr  LOOP  seq-stats  END  LOOP
             opt-id  ;
229       |  .atmark  opt-unit-label  WHILE  expr  LOOP  seq-stats  END
             LOOP  opt-id  ;

230  for-loop
        ::=  opt-unit-label  FOR  name  IN  discrete-range  LOOP
             seq-stats  END  LOOP  opt-id  ;
231       |  .atmark  opt-unit-label  FOR  name  IN  discrete-range
             LOOP  seq-stats  END  LOOP  opt-id  ;

232  exit-stat
        ::=  EXIT  opt-dotted-name  opt-when-cond  ;
233       |  .atmark  EXIT  opt-dotted-name  opt-when-cond  ;

234  opt-dotted-name
        ::=
235       |  dotted-name

236  opt-when-cond
        ::=
237       |  WHEN  expr

238  proc-call-stat
        ::=  name  ;
239       |  .atmark  name  ;

240  return-stat
        ::=  RETURN  ;
241       |  .atmark  RETURN  ;
242       |  RETURN  expr  ;
243       |  .atmark  RETURN  expr  ;

244  wait-stat
        ::=  WAIT  opt-sensitivity-clause  opt-condition-clause
             opt-timeout-clause  ;
245       |  .atmark  WAIT  opt-sensitivity-clause
             opt-condition-clause  opt-timeout-clause  ;

246  opt-sensitivity-clause
        ::=
247       |  sensitivity-clause

248  sensitivity-clause
        ::=  ON  sensitivity-list
```

```
249  sensitivity-list
        ::=  name-list

250  name-list
        ::=  name
251       |  name-list  ,  name

252  opt-condition-clause
        ::=
253       |  condition-clause

254  condition-clause
        ::=  UNTIL  expr

255  opt-timeout-clause
        ::=
256       |  timeout-clause

257  timeout-clause
        ::=  FOR  expr

258  expr-list
        ::=  expr
259       |  expr-list  ,  expr

260  opt-expr
        ::=
261       |  expr

262  expr
        ::=  rel
263       |  rel  and-expr
264       |  rel  nand-expr
265       |  rel  or-expr
266       |  rel  nor-expr
267       |  rel  xor-expr

268  rel
        ::=  simple-expr
269       |  simple-expr  relop  simple-expr

270  and-expr
        ::=  and-part
271       |  and-part  and-expr

272  and-part
        ::=  AND  rel

273  nand-expr
        ::=  nand-part
274       |  nand-part  nand-expr

275  nand-part
        ::=  NAND  rel

276  or-expr
```

```
       ::=  or-part
277      |  or-part  or-expr

278  or-part
       ::=  OR  rel

279  nor-expr
       ::=  nor-part
280      |  nor-part  nor-expr

281  nor-part
       ::=  NOR  rel

282  xor-expr
       ::=  xor-part
283      |  xor-part  xor-expr

284  xor-part
       ::=  XOR  rel

285  simple-expr
       ::=  simple-expr1
286      |  +  simple-expr1
287      |  -  simple-expr1

288  simple-expr1
       ::=  term
289      |  simple-expr1  addop  term

290  term
       ::=  factor
291      |  term  mulop  factor

292  factor
       ::=  primary
293      |  primary  **  primary
294      |  ABS  primary
295      |  NOT  primary

296  primary
       ::=  primary1
297      |  aggregate
298      |  (  expr  )

299  primary1
       ::=  literal
300      |  .atmark
301      |  name

302  literal
       ::=  boolean-literal
303      |  bit-literal
304      |  character-literal
305      |  numeric-literal
306      |  time-literal
307      |  bitstring-literal
308      |  string-literal
```

```
309  boolean-literal
        ::=  FALSE
310       |  TRUE

311  bit-literal
        ::=  .bit

312  character-literal
        ::=  .char

313  numeric-literal
        ::=  .constant

314  time-literal
        ::=  opt-time-constant  time-unit

315  opt-time-constant
        ::=
316       |  .constant

317  time-unit
        ::=  FS
318       |  PS
319       |  NS
320       |  US
321       |  MS
322       |  SEC
323       |  MIN
324       |  HR

325  bitstring-literal
        ::=  .bitstring
326       |  .octstring
327       |  .hexstring

328  string-literal
        ::=  .string

329  aggregate
        ::=  (  2-expr-list  )

330  2-expr-list
        ::=  expr  ,  expr
331       |  2-expr-list  ,  expr

332  target
        ::=  name

333  name
        ::=  name1

334  name1
        ::=  selector
335       |  name1  .  selector
336       |  name1  (  expr-list  )
```

```
337  selector
        ::=  .id

338  relop
        ::=  =
339        |  /=
340        |  <
341        |  <=
342        |  >
343        |  >=

344  addop
        ::=  +
345        |  -
346        |  &

347  mulop
        ::=  *
348        |  /
349        |  MOD
350        |  REM
```

5.2.2 Abstract Syntax: Phase 1

The abstract syntax of Stage 3 VHDL used during Phase 1 translation is shown below.

The superscript "*" denotes Kleene closure (e.g. "decl*" denotes zero or more occurrences of the syntactic object "decl"), and a superscript "+" denotes one or more occurrences. In a syntactic clause, subscripts denote (possibly) different objects of the same class.

As in the concrete syntax, terminal symbols appear in upper case, while all other symbols are either nonterminals or pseudo-terminals (id, bitlit, and constant).

STAGE 3 VHDL ABSTRACT SYNTAX: PHASE 1

```
design-file ::= DESIGN-FILE id pkg-decl* pkg-body* use-clause* ent-decl arch-body

pkg-decl ::= PACKAGE id decl* opt-id

pkg-body ::= PACKAGEBODY id decl* opt-id

use-clause ::= USE dotted-name+
dotted-name ::= id+

ent-decl ::= ENTITY id port-decl* decl* opt-id

arch-body ::= ARCHITECTURE id1 id2 decl* con-stat* opt-id

port-decl ::= DEC    PORT id+ mode type-mark  opt-expr
            | SLCDEC PORT id+ mode slice-name opt-expr
```

```
mode ::= IN | OUT | INOUT | BUFFER

type-mark ::= dotted-name

slice-name ::= type-mark discrete-range

discrete-range ::= direction expr1 expr2
direction ::= TO | DOWNTO

arch-body ::= ARCHITECTURE id1 id2 decl* con-stat* opt-id

decl ::= object-decl
       | type-decl
       | subtype-decl
       | pkg-decl
       | pkg-body
       | subprog-decl
       | subprog-body
       | use-clause

object-decl ::= DEC    object-class id+ type-mark  opt-expr
              | SLCDEC object-class id+ slice-name opt-expr

object-class ::= CONST | VAR | SIG

type-decl ::= enum-type-decl
            | array-type-decl
            | integer-type-decl

enum-type-decl ::= ETDEC id id+

array-type-decl ::= ATDEC id discrete-range type-mark

integer-type-decl ::= ITDEC id discrete-range

subtype-decl ::= STDEC id type-mark opt-discrete-range

subprog-decl ::= subprog-spec

subprog-spec ::= PROCEDURE id proc-par-spec* type-mark
               | FUNCTION  id func-par-spec* type-mark

proc-par-spec ::= object-class id+ proc-par-mode type-mark opt-expr
func-par-spec ::= object-class id+ func-par-mode type-mark opt-expr
```

```
proc-par-mode ::= IN | OUT | INOUT
func-par-mode ::= IN

subprog-body ::= SUBPROGBODY subprog-spec decl* seq-stat* opt-id

con-stat ::= process-stat
           | selected-sig-assn-stat
           | conditional-sig-assn-stat

process-stat ::= PROCESS id ref* decl* seq-stat* opt-id

selected-sig-assn-stat ::= SEL-SIGASSN delay-type id expr ref selected-waveform+
selected-waveform ::= SEL-WAVE waveform discrete-range+

conditional-sig-assn-stat ::= COND-SIGASSN delay-type id ref cond-waveform* waveform
cond-waveform ::= COND-WAVE waveform expr

seq-stat ::= null-stat
           | var-assn-stat
           | sig-assn-stat
           | if-stat
           | case-stat
           | loop-stat
           | while-stat
           | for-stat
           | exit-stat
           | call-stat
           | return-stat
           | wait-stat

null-stat ::= NULL

var-assn-stat ::= VARASSN ref expr

sig-assn-stat ::= SIGASSN delay-type ref waveform

delay-type ::= INERTIAL | TRANSPORT

waveform ::= WAVE transaction+
transaction ::= TRANS expr opt-expr

if-stat ::= IF cond-part+ else-part
cond-part ::= expr seq-stat*
else-part ::= seq-stat*

case-stat ::= CASE expr case-alt+
```

```
case-alt ::= CASECHOICE discrete-range+ seq-stat*
           | CASEOTHERS seq-stat*

loop-stat ::= LOOP id seq-stat* opt-id

while-stat ::= WHILE id expr seq-stat* opt-id

for-stat ::= FOR id ref discrete-range seq-stat* opt-id

exit-stat ::= EXIT opt-dotted-name opt-expr

call-stat ::= CALL ref

return-stat ::= RETURN opt-expr

wait-stat ::= WAIT ref* opt-expr1 opt-expr2

expr ::= ϵ
       | bool-lit
       | bit-lit
       | num-lit
       | time-lit
       | char-lit
       | bitstr-lit
       | str-lit
       | ref
       | positional-aggregate
       | unary-op expr
       | binary-op expr1 expr2
       | relational-op expr1 expr2

bool-lit ::= FALSE | TRUE

bit-lit ::= BIT bitlit

num-lit ::= NUM constant

time-lit ::= TIME constant time-unit

char-lit ::= CHAR constant

bitstr-lit ::= BITSTR bit-lit*

str-lit ::= STR char-lit*

ref ::= REF name
```

```
name ::= id
       | name id
       | name expr*

positional-aggregate ::= PAGGR expr*

unary-op ::= NOT | PLUS | NEG | ABS

binary-op ::= AND | NAND | OR  | NOR | XOR
            | ADD | SUB  | MUL | DIV | MOD | REM | EXP
            | CONCAT

relational-op ::= EQ | NE | LT | LE | GT | GE

time-unit ::= FS | PS | NS | US | MS | SEC | MIN | HR

opt-id ::= ϵ | id

opt-discrete-range ::= ϵ | discrete-range

opt-dotted-name ::= ϵ | dotted-name

opt-expr ::= ϵ | expr
```

5.2.3 Abstract Syntax: Phase 2

The abstract syntax of Stage 3 VHDL used during Phase 2 translation differs in certain respects from that employed by Phase 1, at exactly those points indicated below.

The abstract syntax transformation occurs at the very end of Phase 1, and just prior to the invocation of Phase 2, as described in Section 7.

The most significant transformations of Phase 1 syntax to that of Phase 2 are: (1) the "desugaring" (i.e., reduction to more basic constructs) of concurrent signal assignment statements (conditional signal assignment and selected signal assignment) into equivalent PROCESS statements; and (2) the disambiguation of REFs into simple references, array references, record field accesses (not fully supported by Stage 3 VHDL), and subprogram calls.

STAGE 3 VHDL ABSTRACT SYNTAX: PHASE 2

```
ent-decl ::= ENTITY id decl*_1 decl*_2 opt-id phase1-hook

con-stat ::= process-stat
```

```
process-stat ::= PROCESS id decl* seq-stat* opt-id phase1-hook

expr ::= ϵ
       | bool-lit
       | bit-lit
       | num-lit
       | time-lit
       | char-lit
       | enum-lit
       | bitstr-lit
       | str-lit
       | ref
       | positional-aggregate
       | type-conversion
       | unary-op expr
       | binary-op expr1 expr2
       | relational-op expr1 expr2

time-lit ::= TIME constant FS

enum-lit ::= ENUMLIT id

ref ::= REF modifier+

modifier ::= SREF id+ id
           | INDEX expr
           | SELECTOR id
           | PARLIST expr*

type-conversion ::= TYPECONV expr type-mark

unary-op ::= NOT | BNOT | PLUS | NEG | ABS | RNEG | RABS

binary-op ::= AND   | NAND   | OR     | NOR  | XOR
            | BAND  | BNAND  | BOR    | BNOR | BXOR
            | ADD   | SUB    | MUL    | DIV  | MOD  | REM | EXP
            | RPLUS | RMINUS | RTIMES | RDIV | REXPT
            | CONCAT

relational-op ::= EQ  | NE  | LT  | LE | GT | GE
                | RLT | RLE | RGT | RGE
```

The occurrences of `phase1-hook` in the Phase 2 abstract syntax for `ent-decl` and `process-stat` point to the Phase 1 abstract syntax for the respective constructs, for the purposes of the SDVS VHDL Symbolic Execution Trace Window.

6 Phase 1: Static Semantic Analysis and Environment Collection

Now that the necessary background has been established, we are ready to examine the formal description of the Stage 3 VHDL translator.

In this section, an overview of Phase 1 and its relation to Phase 2 will be presented, followed by detailed discussions of the environment manipulated by the translator and the Phase 1 semantic domains and function types, and finally the Phase 1 semantic equations themselves.

6.1 Overview

A Stage 3 VHDL hardware description is first parsed according to the Stage 3 VHDL concrete grammar, producing an *abstract syntax tree* that serves as the input to Phase 1 translation.

Phase 1 of the translation accomplishes the following.

- Performs static semantic checks to verify that certain conditions are met, including:
  - Objects, subprograms, packages, and process and loop labels must be declared prior to use.
  - Identifiers with the same name cannot be declared in the same local context.
  - References to objects and labels must be proper, e.g. scalar objects must not be indexed, array references must have the correct number of indices, and `EXIT` statements must reference a loop label.
  - All components of statements and expressions must have the proper type, e.g. expressions used as conditions must be boolean, array indices must be of the proper type, operators must receive operands of the correct type, procedure and function calls must receive actual parameters of the proper type, function calls must return a result of a type appropriate for their use in an expression.
  - Sensitivity lists in `PROCESS` and `WAIT` statements must contain signal identifiers.
  - The collection of discrete ranges defining a `CASE` statement alternative must be exhaustive and mutually exclusive.
  - The time delays in the `AFTER` clause of a signal assignment statement must be increasing.
- Creates a new *abstract syntax tree* — a transformed version of the original abstract syntax tree (used by Phase 1) — that will be more conveniently utilized by Phase 2 of the translation.
- Creates and manipulates a *tree-structured environment (TSE)* that, in the absence of errors, is provided to Phase 2 of the translation.

If the VHDL translator completes Phase 1 without error, then it can proceed with Phase 2, *state delta generation*. Phase 2 requires two inputs: the transformed abstract syntax tree and the tree-structured environment for the hardware description, both constructed by Phase 1.

The tree-structured environment contains a complete record of the name/attribute associations corresponding to the hardware description's declarations, and its structure reflects that of the description. Referring to this TSE, Phase 2 incrementally generates and (per user proof commands) applies state deltas via symbolic execution and the theories built into the Simplifier.

6.2 Descriptors, Types, and Type Modes

When a declaration of an identifier is processed by Phase 1, that identifier is bound in the TSE to a *descriptor*, a structured object that contains the attributes of the identifier instance associated to it by that declaration.

At the time a descriptor is created and entered into the TSE, its **qid** field is set to ϵ. The value of the **qid** field is eventually set to the proper *statically uniquely qualified name* (*SUQN*), when such a qualified name makes sense; see Section 8.2.1. These updates to the **qid** fields become possible only once the TSE is fully constructed, i.e., at the very end of Phase 1 — or in other words, at the very beginning of Phase 2, the phase in which these uniquely qualified names are needed.

Eight kinds of descriptor are used in Phase 1: *object*, *package*, *process name*, *loop name*, *function*, *procedure*, *enumeration type element*, and *type*. Their structures are as follows:

object :

< id, qid, tag, path, exported, type, value, process >

The **id** field contains the identifier to which this descriptor is bound, and the **qid** field contains its statically uniquely qualified name (SUQN). The **tag** field contains ***OBJECT***. The **path** field contains the path in the tree-structured environment to the component environment in which this instance of the identifier is bound. The **exported** field indicates whether the definition of this identifier instance can be exported to other environments. A value **true** (represented by DENOTE symbol **tt**) indicates exportation is permitted, and a value **false** (represented by DENOTE symbol **ff**) indicates that it is not. This becomes an issue when the declaration whose elaboration created this descriptor was contained in a package specification (exportable) or package body (not exportable).

If the identifier **id** represents a constant initialized via a *static* expression, then the **value** field contains the initial value; otherwise it contains ***UNDEF*** (undefined). Array and record references *never* represent static values in VHDL, so the **value** field of corresponding object descriptors contains ***UNDEF***.

If the identifier **id** represents a signal, then the label of the first `PROCESS` statement in which **id** is the target of a signal assignment is entered into the **process** field, to enable the detection of assignments to the signal by multiple processes (disallowed in Stage 3 VHDL).

Finally, the object descriptor's **type** field contains the *type* of the identifier, represented by a pair < **tmode, tdesc** >:

- **tmode** is the *type mode*, itself a pair;
  normally,

  tmode = <object-class, ref-mode>,

  where **object-class** $\in$ {**CONST, VAR, SIG**}
  and **ref-mode** $\in$ {**VAL, REF, OUT**}.

  The **tmode** indicates, first, whether the object is a constant (**object-class = CONST**), variable (**object-class = VAR**), or signal (**object-class = SIG**), and second, whether the object is read-only (**ref-mode = VAL**), read-write (**ref-mode = REF**), or write-only (**ref-mode = OUT**).

  For technical purposes, it is also occasionally convenient for Phase 1 translation to manipulate "dummy" type modes of the form < **DUMMY, VAL** >, < **DUMMY, OBJ** >, < **DUMMY, ACC** >, < **DUMMY, AGR** >, and < **DUMMY, TYP** >, as well as "path" type modes of the form < **PATH, p** > where **p** is a path in the TSE.
- **tdesc** is the *type descriptor* (see below). It gives the object's *basic type*, irrespective of the type mode.

To introduce a bit more terminology, a type in which the **ref-mode** is **REF** or **OUT** will be called a *reference type*, while one whose **ref-mode** is **VAL** will be called a *value type*. A reference type indicates that the associated object can have its value altered (by an assignment, say), as opposed to a value type.

Finally, the type descriptor **d = tdesc** is the *basic type* of the type < **tmode, tdesc** > of which it is the second component.

package :

< id, qid, *PACKAGE*, path, exported, pbody >

The **id**, **qid**, **path**, and **exported** fields are as above. The tag field contains ***PACKAGE***. If this package has a body, the **pbody** field contains the transformed abstract syntax tree of the package body; otherwise it contains ϵ.

process name :

< id, qid, *PROCESSNAME*, path >

The **id** and **path** fields are as above. The tag field contains ***PROCESSNAME*** (the process label). The **qid** field has no relevance here, and contains ϵ.

loop name :

< id, qid, *LOOPNAME*, path >

The **id**, **qid**, and **path** fields are as in a process name. The tag field contains ***LOOPNAME*** (the loop label).

function :

< id, qid, *FUNCTION*, path, exported, signatures, body, characterizations >

The **id**, **qid**, **exported**, and **path** fields are as above. The **tag** field contains ***FUNCTION***.

The **signatures** field contains a list of signatures, that is, < **pars**, **rtype** > pairs; this list will be a singleton unless the function is overloaded. The **pars** field of a signature is a list that indicates the names and types of the function's formal parameters. Each list element is a pair, whose first component is the identifier that denotes the formal parameter's name and whose second component is its type. The **rtype** (result type) field of a signature contains the type of the function's result for these particular parameter types; this type is always a *value type*.

The **body** field of a function descriptor contains the transformed abstract syntax tree of the function's body (including its local declarations) if a body exists, and ϵ otherwise. The **characterizations** field of a function descriptor always contains ϵ (see procedure descriptors for a description of this field).

procedure :

< **id**, **qid**, ***PROCEDURE***, **path**, **exported**, **signatures**, **body**, **characterizations** >

The **id**, **qid**, **path**, **exported**, **signatures**, **body**, and **characterizations** fields are as in the function descriptor. The **tag** field contains ***PROCEDURE*** (procedure). Since procedures return no result, all **rtype** fields in each **signature** contain the *void* standard value type (see below).

The **characterizations** field of a procedure descriptor, unlike that of a function descriptor, is potentially nonempty. One of either the **body** or the **characterizations** must contain ϵ; either a procedure has a body that may be symbolically executed, or it has been characterized by a set of state deltas.

A characterization is a 6-tuple containing the following information:

- the path to the procedure;
- the identifier that names the procedure;
- a list of the identifiers that name the arguments to the procedure;
- a (possibly empty) precondition that determines under which conditions this characterization may be used;
- a modification list of the names of variables changed by this procedure; and
- a postcondition that states the effects of the procedure.

The last three items in the tuple must be given in SDVS internal state delta notation, as they form the basis for a state delta that characterizes the actions of the procedure.

enumeration type element :

< **id**, **qid**, ***ENUMELT***, **path**, **exported**, **type** >

The **id** field contains the name of an enumeration type element, the **tag** field is ***ENUMELT***, and the **type** field contains the descriptor of the enumeration type.

type :

There are six kinds of type descriptor: those for *standard types*, *enumeration types*, *array types*, *subtypes*, *integer definition types*, and *record types*. Although record

types are not actually incorporated in the Stage 3 VHDL language subset, the Stage 3 VHDL translator contains support for their eventual implementation.

Each type descriptor has an **id** field (containing the *name* of that type), a corresponding **qid** field, a **tag** field (indicating the kind of type descriptor), **path** and **exported** fields (that serve the usual purpose), and additional fields that contain information appropriate to the type represented by the descriptor. The detailed structures of the type descriptors are as follows:

standard type :

< **id, qid, tag, path, exported** >

Standard types are those considered to be predeclared; they are always exportable. In Stage 3 VHDL, the standard types are *boolean*, *bit*, *integer*, *real*, *time*, *character*, *bit_vector*, and *string*; they cannot be redeclared.

The **id** and **tag** fields denote the following Stage 3 VHDL standard types:

id = BOOLEAN, **tag = *BOOL***

id = BIT, **tag = *BIT***

id = UNIVERSAL_INTEGER, **tag = *INT***

id = INTEGER, **tag = *INT***

id = REAL, **tag = *REAL***

id = TIME, **tag = *TIME***

id = BIT_VECTOR, **tag = *ARRAYTYPE***

id = STRING, **tag = *ARRAYTYPE***

For completeness, we also provide *void* and *polymorphic* standard types for Stage 3 VHDL:

id = VOID, **tag = *VOID***

id = POLY, **tag = *POLY***

Functions are available that look up the type descriptors for the standard types; during translation Phase 1, these type descriptors are bound to the type identifiers in the **t((STANDARD))** component environment of the TSE **t**:

bool-type-desc(t) = t((**STANDARD**))(**BOOLEAN**)

bit-type-desc(t) = t((**STANDARD**))(**BIT**)

univint-type-desc(t) = t((**STANDARD**))(**UNIVERSAL_INTEGER**)

int-type-desc(t) = t((**STANDARD**))(**INTEGER**)

real-type-desc(t) = t((**STANDARD**))(**REAL**)

time-type-desc(t) = t((**STANDARD**))(**TIME**)

void-type-desc(t) = t((**STANDARD**))(**VOID**)

poly-type-desc(t) = t((**STANDARD**))(**POLY**)

In each of the above cases, the type descriptor has the form:

< **id, epsilon, tag, (STANDARD), tt, lb, ub** >

char-type-desc(t) = t((**STANDARD**))(**CHARACTER**)

The type descriptor for the **CHARACTER** type has the form:

< **CHARACTER, epsilon, *ENUMTYPE*, (STANDARD), tt, (CHAR 0), (CHAR 127), literals** >

bitvector-type-desc(t) = t((**STANDARD**))(**BIT_VECTOR**)

The type descriptor for the **BIT_VECTOR** type has the form:

< **BIT_VECTOR, epsilon, *ARRAYTYPE*, (STANDARD), tt, TO, (NUM 0), epsilon, bittypedesc** >

string-type-desc(t) = t((**STANDARD**))(**STRING**)

The type descriptor for the **STRING** type has the form:

< **STRING, epsilon, *ARRAYTYPE*, (STANDARD), tt, TO, (NUM 1), epsilon, chartypedesc** >

enumeration type :

< **id, qid, *ENUMTYPE*, path, exported, literals** >

The **literals** field is a nonempty list of identifiers giving the enumeration literals (in order) for this type. Both characters and identifiers are admissible enumeration literals in Stage 3 VHDL.

array type :

< **id, qid, *ARRAYTYPE*, path, exported, direction, lb, ub, elty** >

Every array type has a name; unique names are generated for anonymous array types. Arrays in Stage 3 VHDL are *one-dimensional*, of index type **UNIVERSAL_INTEGER**. Note that the standard types **BIT_VECTOR** and **STRING** are array types.

The **direction** field contains either **TO** or **DOWNTO**, indicating whether the indices of the array increase or decrease, respectively. The **lb** and **ub** fields contain, respectively, abstract syntax trees for expressions that denote the array type's lower and upper bounds. The **elty** (element type) field contains the descriptor of the type of the array's elements. The values of the array's lower and upper bounds are not necessarily static; therefore, array bounds-checking generally cannot be performed in Phase 1, but must be deferred to Phase 2 ("run time"), when state deltas are applied ("executed").

The following function accepts arguments for the creation of an array type:

array-type-desc(array-name,qid,path,exported,direction,lower-bound,upper-bound,element-type)
= <array-name,qid,***ARRAYTYPE*** ,path,exported,direction,lower-bound,upper-bound,element-type>

subtype :

< id, qid, *SUBTYPE*, path, exported, lb, ub, basetype >

The **lb** and **ub** fields contain, respectively, abstract syntax trees for expressions that denote the subtype's lower and upper bounds. The **basetype** field contains the descriptor of the subtype's base type.

integer definition type :

< id, qid, *INT_TYPE*, path, exported, lb, ub, parenttype >

The **lb** and **ub** fields contain, respectively, abstract syntax trees for expressions that denote the integer definition type's lower and upper bounds. The **parenttype** field contains the descriptor of the integer definition type's parent type, which is always **UNIVERSAL_INTEGER**.

record type :

< id, qid, *RECORDTYPE*, path, exported, components >

The **components** field is a nonempty list of triplets; each triplet represents a field of this record type. The first element of each triplet is an identifier that is this field's name. The second element is a descriptor representing this field's basic type. The third element either is empty or contains an abstract syntax tree for Phase 2 initialization for components of objects declared to be of this record type. As noted above, records are not implemented as part of Stage 3 VHDL, and record types are included simply in preparation for the anticipated implementation of records.

6.2.1 Type and type descriptor predicates

Predicates are available for distinguishing specific types and type descriptors:

is-boolean?(type) = is-boolean-tdesc?(tdesc(type))

is-boolean-tdesc?(d) = idf(d)= **BOOLEAN**

is-bit?(type) = is-bit-tdesc?(tdesc(type))

is-bit-tdesc?(d) = idf(d)= **BIT**

is-integer?(type) = is-integer-tdesc?(tdesc(type))

is-integer-tdesc?(d) = tag(d)∈ **(*INT* *INT_TYPE*)**

is-real?(type) = is-real-tdesc?(tdesc(type))

is-real-tdesc?(d) = idf(d)= **REAL**

is-time?(type) = is-time-tdesc?(tdesc(type))

is-time-tdesc?(d) = idf(d)= **TIME**

is-void?(type) = is-void-tdesc?(tdesc(type))

is-void-tdesc?(d) = idf(d)= **VOID**

is-poly?(type) = is-poly-tdesc?(tdesc(type))

is-poly-tdesc?(d) = idf(d)= **POLY**

is-character?(type) = is-character-tdesc?(tdesc(type))

is-character-tdesc?(d) = idf(d)= **CHARACTER**

is-array?(type) = is-array-tdesc?(tdesc(type))

is-array-tdesc?(d) = tag(d)= ***ARRAYTYPE***

is-record?(type) = is-record-tdesc?(tdesc(type))

is-record-tdesc?(d) = tag(d)= ***RECORDTYPE***

is-bitvector?(type) = is-bitvector-tdesc?(tdesc(type))

is-bitvector-tdesc?(d)
= **let** idf = idf(d) **in**
idf = **BIT_VECTOR** ∨ (consp(idf)∧ hd(idf)= **BIT_VECTOR**)

is-string?(type) = is-string-tdesc?(tdesc(type))

is-string-tdesc?(d)
= **let** idf = idf(d) **in**
idf = **STRING** ∨ (consp(idf)∧ hd(idf)= **STRING**)

is-const?(type) = object-class(tmode(type))= **CONST**

is-var?(type) = object-class(tmode(type))= **VAR**

is-sig?(type) = object-class(tmode(type))= **SIG**

6.2.2 Additional primitive accessors and predicates

Certain primitive functions can be applied to descriptors. For each kind of descriptor and field there exists an access function, ordinarily with the same name as the field (the only exception being **idf** instead of **id**). When applied to a descriptor of the proper kind, the access function extracts the contents of that descriptor's corresponding field. For example, if **d** is an object descriptor, then **tag(d)** = ***OBJECT***.

If **d** is any descriptor, then the fully qualified name of the corresponding identifier instance is returned by function **namef**:

namef(d) = $(path(d))(idf(d))

Defined below are the descriptor component access functions, a few related constructor and access functions, and some convenient additional predicates.

idf(d) = hd(d)

qid(d) = hd(tl(d))

tag(d) = hd(tl(tl(d)))

path(d) = hd(tl(tl(tl(d))))

exported(d) = hd(tl(tl(tl(tl(d)))))

type-tick-low(d) = hd(tl(tl(tl(tl(tl(d))))))

type-tick-high(d) = hd(tl(tl(tl(tl(tl(tl(d)))))))

base-type(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

parent-type(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

literals(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

pbody(d) = hd(tl(tl(tl(tl(tl(d))))))

type(d) = hd(tl(tl(tl(tl(tl(d))))))

value(d) = hd(tl(tl(tl(tl(tl(tl(d)))))))

process(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

signatures(d) = hd(tl(tl(tl(tl(tl(d))))))

body(d) = hd(tl(tl(tl(tl(tl(tl(d)))))))

characterizations(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

direction(d) = hd(tl(tl(tl(tl(tl(d))))))

lb(d) = hd(tl(tl(tl(tl(tl(tl(d)))))))

ub(d) = hd(tl(tl(tl(tl(tl(tl(tl(d))))))))

elty(d) = hd(tl(tl(tl(tl(tl(tl(tl(tl(d)))))))))

components(d) = hd(tl(tl(tl(tl(tl(d))))))

pars(signature) = hd(signature)

rtype(signature) = hd(tl(signature))

get-base-type(d) = (tag(d)= ***SUBTYPE*** → base-type(d), d)

get-parent-type(d)
= (tag(d)∈ (***INT_TYPE* *DERIVED_TYPE***) → parent-type(d),
    error(cat("Not a derived type: ")(d)))

mk-type(tmode)(tdesc) = (tmode,tdesc)

tmode(type) = hd(type)

tdesc(type) = hd(tl(type))

mk-tmode(object-class)(ref-mode) = (object-class,ref-mode)

object-class(tmode) = hd(tmode)

ref-mode(tmode) = hd(tl(tmode))

is-const?(type) = object-class(tmode(type))= **CONST**

is-var?(type) = object-class(tmode(type))= **VAR**

is-sig?(type) = object-class(tmode(type))= **SIG**

is-readable?(type) = ref-mode(tmode(type))∈ **(VAL REF)**

is-writable?(type) = ref-mode(tmode(type))∈ **(REF OUT)**

is-ref?(expr) = hd(expr)= **REF**

is-paggr?(expr) = hd(expr)= **PAGGR**

is-unary-op?(op) = op ∈ **(NOT PLUS NEG ABS)**

is-binary-op?(op)
= op ∈ **(AND NAND OR NOR XOR ADD SUB MUL DIV MOD REM EXP CONCAT)**

is-relational-op?(op) = op ∈ **(EQ NE LT LE GT GE)**

6.3 Special-Purpose Environment Components and Functions

Certain component environments **r** of the tree-structured environment (TSE) part of the translation state have special identifier-like names that are bound to values specific to that environment's associated program unit (design file, package, entity, architecture, process, procedure, function, or loop):

UNIT :

r(*UNIT*) contains a tag that identifies what kind of program unit led to the creation of **r**. These tags are ***DESIGN-FILE*** (design file), ***PACKAGE*** (package), ***ENTITY*** (entity), ***ARCHITECTURE*** (architecture), ***PROCESS*** (process), ***PROCEDURE*** (procedure), ***FUNCTION*** (function), and ***LOOP*** (loop). These tags are used to locate the innermost instance of a specific kind of environment (such as one associated with a process) on the current lookup path in the TSE.

LAB :

When the **tag** of **r(*UNIT*)** is ***ARCHITECTURE***, the value bound to **r(*LAB*)** contains an identifier list of all the process labels declared in the program unit. When the **tag** of **r(*UNIT*)** is ***PROCESS***, ***PROCEDURE***, ***FUNCTION***, or ***LOOP***, the value bound to **r(*LAB*)** contains an identifier list of all the loop labels declared in the program unit. These lists are used to ensure that the identifiers serving as process and loop labels are distinct in (the top-level scope of) each program unit.

USED :

The environment corresponding to any program unit admitting `USE` clauses in its declarative part has a ***USED*** component. In this case, **r(*USED*)** is a list representing the set of fully qualified names of packages named in `USE` clauses appearing in that declarative part, omitting the qualified names of packages that textually enclose those `USE` clauses. In order to ensure that the TSE used in Phase 2 of the Stage 3 VHDL translator can remain *fixed* as that generated by Phase 1, a slight restriction is imposed on the concrete syntax of Stage 3 VHDL. This restriction requires that *all* of the `USE` clauses in a declarative part appear only at the *end* of that declarative part. This will be discussed more fully later.

IMPT :

Whenever a program unit has a ***USED*** component, it also has a ***IMPT*** component. **r(*IMPT*)** is a list of the fully qualified names of those items that can be imported into the program unit's environment by the elaboration of the `USE` clauses in its declarative part. Consequently, no two of these fully qualified names can have the same last identifier (unqualified name), nor can the last identifier of any of these fully qualified names be the same as an identifier whose (local) declaration appears in this program unit's declarative part.

SENS :

When the **tag** of **r(*UNIT*)** is ***PROCESS***, the value bound to **r(*SENS*)** con-

tains a list of the transformed abstract syntax trees of the **refs** appearing in that process' sensitivity list. Phase 1 translation of a `WAIT` statement occurring in a `PROCESS` statement checks to make sure this ***SENS*** list is empty; otherwise, the `WAIT` occurs illegally in a process with a sensitivity list.

Special Phase 1 Functions

Three special-purpose Phase 1 functions defined by SDVS are **set-difference**, **new-array-type-name**, and **delete-duplicates**; these are provided by SDVS because of the difficulty of writing their definitions in the DENOTE language (DL).

Function **set-difference** returns the set difference of two lists. Function **new-array-type-name** returns a new unique name for an anonymous array type. Function **delete-duplicates** destructively deletes duplicate items from a list.

Error Reporting

Phase 1 errors are reported by three SDVS functions: **error**, which takes a string-valued error message; **error-pp**, which takes a string-valued error message and an additional VHDL abstract syntax subtree to be pretty-printed; and **cat**, which makes a string from its (variable number of) arguments, each of which is made into a string.

6.4 Phase 1 Semantic Domains and Functions

The formal description of Phase 1 translation consists of *semantic domains* and *semantic functions*, the latter being functions from syntactic to semantic domains. *Compound semantic domains* are defined in terms of *primitive semantic domains*. Similarly, *primitive semantic functions* are unspecified (their definitions being understood implicitly) and the remaining semantic functions are defined (by syntactic cases) via *semantic equations*.

The principal Phase 1 semantic functions (and corresponding Stage 3 VHDL language constructs for which they perform static analysis) are: **DFT** (design files), **ENT** (entity declarations), **ART** (architecture bodies), **PDT** (port declarations), **DT** (declarations), **CST** (concurrent statements), **SLT** (sensitivity lists), **SST** (sequential statements), **AT** (case alternatives), **DRT** (discrete ranges), **WT** (waveforms), **TRT** (transactions), **MET** (reference lists), **ET** and **RT** (expressions), **OT1** (unary operators), **OT2** (binary and relational operators), **B** (bit literals), and **N** (numeric literals).

Each of the principal semantic functions requires an appropriate *syntactic argument* — an abstract syntactic object (tree) generated by the Stage 3 VHDL language parser. Most of the semantic functions take (at least) the following additional arguments:

- a *path*, indicating the currently visible portion of the (partially constructed) tree-structured environment;
- a *continuation*, specifying which Phase 1 semantic function to invoke next; and

- a (partially constructed) TSE, containing the information gathered from declarations previously elaborated and checked.

In the absence of errors, the Phase 1 semantic functions update the TSE. Moreover, **ET** and **RT** also construct a pair consisting of an expression's type and its *static value*. The type is either a *value type* or a *reference type*; see Section 6.2. Only an expression with a reference type may be the target of an assignment operation.

An expression's static value is ***UNDEF*** ("undefined") unless it is a *static* expression, in which case its static value is determined as follows. A *static expression* is:

- a boolean, bit, numeric, or character literal: the static value is the value of the corresponding constant;
- an identifier explicitly declared as a scalar constant and initialized by a static expression: the static value is the static value of the initialization expression;
- an operator applied to operands that are static expressions: the static value is determined by the semantics of the operator and the static value of the operands;
- a static expression enclosed in parentheses: the static value is the static value of the enclosed static expression.

Note that a subscripted array reference, even if the subscript is a static expression and the array was declared as a constant initialized with a list of static expressions, is *not* a static expression. (The same is true for a selected record component.)

6.4.1 Phase 1 Semantic Domains

The semantic domains and function types for Phase 1 of the Stage 3 VHDL translator are as follows.

Primitive Semantic Domains

Bool = {**FALSE**, **TRUE**}	boolean constants
Bit = {**0**, **1**}	bit constants
Char = {(**CHAR 0**), ..., (**CHAR 127**)}	character constants (ASCII-128 representations)
n : **N** = {0, 1, 2, ...}	numeric constants (natural numbers)
id : **Id**	identifiers
SysId	system-generated identifiers (disjoint from **Id**)
t : **TEnv**	tree-structured environments (TSEs)
d : **Desc**	descriptors (see Section 6.2)
sd : **SD**	state deltas

Assert SDVS Simplifier assertions

Error error messages

Compound Semantic Domains

elbl : Elbl = Id + SysId TSE edge labels
p, q: Path = Elbl* TSE paths
qname: Name = Elbl (. Elbl)* qualified names

d : Dv = Desc denotable values (descriptors)
r : Env = Id → (Dv + {*UNBOUND*}) environments

Tmode = {PATH} × Id* + type modes
({CONST, VAR, SIG, DUMMY} ×
{VAL, OUT, REF, OBJ, ACC, TYP})

w : Type = Tmode × Desc types
e : Value values

h : CSet = P(Bool) + P(Char) + P_f(N) case selection sets [P(•) denotes "powerset of"
+ {INT} + {ENUM} and P_f(•) denotes "set of finite subsets of"]

u : TDc = TEnv → Ans declaration & concurrent statement continuations
c : TSc = TDc sequential statement continuations
k : TEc = (Type × Value) → TSc expression continuations
h : TMc = (Type* × Value*) → TSc reference list continuations
y : TAc = CSet → TSc case alternative continuations
v : TTc = Type → Ans type continuations
z : Desc → TDc descriptor continuations

Ans = (SD + Assert)* + Error final answers

6.4.2 Phase 1 Semantic Functions

The semantic functions for Phase 1 of the Stage 3 VHDL translator are as follows.

DFT : Design → Ans design file static semantics

ENT : Ent → Path → TDc → TDc entity declaration static semantics
ART : Arch → Path → TDc → TDc architecture body static semantics

PDT : PDec* → Path → Bool → TDc → TDc port declaration static semantics
DT : Dec* → Path → Bool → TDc → TDc declaration static semantics

CST :	**CStat* → Path → TDc → TDc**	concurrent statement static semantics
SLT :	**Ref* → Path → TDc → TDc**	sensitivity list static semantics
SST :	**SStat* → Path → TSc → TSc**	sequential statement static semantics
AT :	**Alt* → Type → Path → TAc → TSc**	case alternative static semantics
DRT :	**Drg → Type → Path → TAc → TSc**	discrete range static semantics
WT :	**Wave → Path → TEc → TSc**	waveform static semantics
TRT :	**Trans* → Path → TEc → TSc**	transaction static semantics
MET :	**Ref* → Path → TMc → TSc**	reference list static semantics
ET :	**Expr → Path → TEc → TSc**	expression static semantics
RT :	**Expr → Path → TEc → TSc**	expression static semantics
OT1 :	**Uop → TEc → TEc**	unary operator static semantics
OT2 :	**Bop → TEc → (Type × Value) → TEc**	binary, relational operator static semantics
B :	**BitLit → Bit**	bit values of bit literals (primitive)
N :	**NumLit → N**	integer values of numeric literals (primitive)

6.5 Phase 1 Semantic Equations

6.5.1 Stage 3 VHDL Design Files

```
(DFT1) DFT ⟦ DESIGN-FILE id pkg-decl* pkg-body* use-clause* ent-decl arch-body ⟧
       = let t0 = mk-initial-tse()
             and p0 = %(ε)(id) in
         let id1 = hd(tl(ent-decl)) in
          let t1 = enter-standard(t0)
              and p1 = %(p0)(id1) in
           let t2 = enter(t1)(ε)(id)(<ε,*DESIGN-FILE* ,ε,tt>) in
            let t3 = enter(extend(t2)(ε)(id))(p0)(*UNIT* )(<ε,*DESIGN-FILE* >) in
             let t4 = enter(t3)(p0)(*LAB* )(<ε,ε>) in
              let t5 = enter(t4)(p0)(*USED* )(<ε,ε>) in
               let t6 = enter(t5)(p0)(*IMPT* )(<ε,ε,ε>) in
                enter-objects
                   ((VHDLTIME ,VHDLTIME_PREVIOUS ))
                   (<ε,*OBJECT* ,ε,tt,
                      ((DUMMY ,VAL ),vhdltime-type-desc(t0)),*UNDEF* ,ε>)(t6)(ε)(u)
                  where
                  u = λt.let use-clause = (USE ,((STANDARD ,ALL ))) in
                          DT ⟦ use-clause ⟧ (ε)(tt)(u1)(t)
                  where u1 = λt.DT ⟦ pkg-decl* ⟧ (p0)(tt)(u2)(t)
                  where u2 = λt.DT ⟦ pkg-body* ⟧ (p0)(tt)(u3)(t)
                  where u3 = λt.DT ⟦ use-clause* ⟧ (p0)(tt)(u4)(t)
                  where u4 = λt.ENT ⟦ ent-decl ⟧ (p0)(u5)(t)
                  where u5 = λt.ART ⟦ arch-body ⟧ (p1)(u6)(t)
                  where
                  u6 = λt.let unit = DFX ⟦ design-file ⟧ (t) in
                           phase2(unit)(t)

enter-standard(t)
= let t1 = enter-package(t)(ε)(STANDARD ) in
    let t2 = enter-package(t1)(ε)(TEXTIO ) in
     let t3 = enter(t2)(ε)(*USED* )(<ε,ε>) in
      let t4 = enter(t3)(ε)(*IMPT* )(<ε,ε,ε>) in
       let t5 = enter-predefined(t4)((STANDARD) ) in
        t5

enter-package(t)(p)(id)
= let p1 = %(p)(id) in
    let package-desc = <ε,*PACKAGE* ,p,tt,ε> in
     let t1 = enter(t)(p)(id)(package-desc) in
      let t2 = enter(extend(t1)(p)(id))(p1)(*UNIT* )(<ε,*PACKAGE* >) in
       let t3 = enter(t2)(p1)(*USED* )(<ε,ε>) in
        let t4 = enter(t3)(p1)(*IMPT* )(<ε,ε,ε>) in
         t4

enter-predefined(t)(p)
= let t1 = enter(t)(p)(BOOLEAN )(<ε,*BOOL* ,(STANDARD) ,tt,FALSE ,TRUE >) in
    let t2 = enter
                (t1)(p)(BIT )
                (<ε,*BIT* ,(STANDARD) ,tt,mk-bit-simp-symbol(0),
                   mk-bit-simp-symbol(1)>) in
     let t3 = enter(t2)(p)(UNIVERSAL_INTEGER )(<ε,*INT* ,(STANDARD) ,tt,ε,ε>) in
      let t4 = enter(t3)(p)(INTEGER )(<ε,*INT* ,(STANDARD) ,tt,ε,ε>) in
       let t5 = enter(t4)(p)(REAL )(<ε,*REAL* ,(STANDARD) ,tt,ε,ε>) in
```

```
        let t6 = enter(t5)(p)(TIME )(<ε,*TIME* ,(STANDARD) ,tt,ε,ε>) in
         let t7 = enter(t6)(p)(VHDLTIME )(<ε,*VHDLTIME* ,(STANDARD) ,tt,ε,ε>) in
          let t8 = enter(t7)(p)(VOID )(<ε,*VOID* ,(STANDARD) ,tt,ε,ε>) in
           let t9 = enter(t8)(p)(POLY )(<ε,*POLY* ,(STANDARD) ,tt,ε,ε>) in
            let t10 = enter
                        (t9)(p)(BIT_VECTOR )
                        (tl(array-type-desc
                              (BIT_VECTOR )(ε)((STANDARD) )(tt)(TO )((NUM 0) )(ε)
                              (bit-type-desc(t8)))) in
              let t11 = enter-characters(t10)(p) in
               let t12 = enter-string(t11)(p) in
                t12

enter-characters(t)(p)
= let id+ = gen-characters(0)(127) in
    let field-values1 = <ε,*ENUMTYPE* ,p,tt,hd(id+),last(id+),id+> in
     let char-type-desc = cons(CHARACTER ,field-values1) in
      let field-values2 = <ε,*ENUMELT* ,p,tt,mk-type((CONST VAL) )(char-type-desc)> in
       enter-objects(id+)(field-values2)(t)(p)(u)
        where u = λt1.enter(t1)(p)(CHARACTER )(field-values1)

enter-string(t)(p)
= let expr = (NUM 1) in
    let string-type-desc = array-type-desc
                             (STRING )(ε)(p)(tt)(TO )(second(EX ⟦ expr ⟧ (p)(t)))(ε)
                             (char-type-desc(t)) in
     enter(t)(p)(STRING )(tl(string-type-desc))


gen-characters(start)(finish)
= (start = finish → ((CHAR ,finish)),
   cons((CHAR ,start),gen-characters(start+1)(finish)))


enter-objects(id*)(field-values)(t)(p)(u)
= (null(id*)→ u(t),
   let id = hd(id*) in
    (t(p)(id)≠ *UNBOUND* → error(cat("Duplicate object declaration: ")($(p)
                                                                        (id))),
     let t1 = enter(t)(p)(id)(field-values) in
      enter-objects(tl(id*))(field-values)(t1)(p)(u)))
```

6.5.2 Entity Declarations

```
(ENT1) ENT ⟦ ENTITY id port-decl* decl* opt-id ⟧ (p)(u)(t)
       = (¬null(opt-id)∧ opt-id ≠ id
          → error
               (cat("Entity declaration ")(id)
                (" ended with incorrect identifier: ")(opt-id)),
          let t1 = enter(t)(p)(id)(<ε,*ENTITY* ,ε,ff>) in
           let p1 = %(p)(id) in
            let t2 = enter(extend(t1)(p)(id))(p1)(*UNIT* )(<ε,*ENTITY* >) in
             let t3 = enter(t2)(p1)(*LAB* )(<ε,ε>) in
              let t4 = enter(t3)(p1)(*USED* )(<ε,ε>) in
               let t5 = enter(t4)(p1)(*IMPT* )(<ε,ε,ε>) in
                PDT ⟦ port-decl* ⟧ (p1)(tt)(u1)(t5)
                 where u1 = λt.DT ⟦ decl* ⟧ (p1)(tt)(u)(t))
```

6.5.3 Architecture Bodies

(ART1) **ART** ⟦ **ARCHITECTURE** id_1 id_2 decl* con-stat* opt-id ⟧ (p)(u)(t)
= (¬null(opt-id)∧ opt-id ≠ id_1
→ error
(cat("Architecture body ")(id_1)
(" ended with incorrect identifier ")(opt-id)),
let d = lookup(t)(p)(id_2) in
(d = ***UNBOUND*** ∨ tag(d)≠ ***ENTITY***
→ error(cat("No entity ")(id_2)(" for architecture body ")(id_1)),
let p_1 = %(p)(id_1) in
let t_1 = enter(t)(p)(id_1)(<ε,***ARCHITECTURE*** ,p,ff>) in
let t_2 = enter(extend(t_1)(p)(id_1))(p_1)(***UNIT***)(<ε,***ARCHITECTURE*** >) in
let t_3 = enter(t_2)(p_1)(***LAB***)(<ε,ε>) in
let t_4 = enter(t_3)(p_1)(***USED***)(<ε,ε>) in
let t_5 = enter(t_4)(p_1)(***IMPT***)(<ε,ε,ε>) in
DT ⟦ decl* ⟧ (p_1)(tt)(u_1)(t_5)
where u_1 = λt_6.**CST** ⟦ con-stat* ⟧ (p_1)(u)(t_6)))

6.5.4 Port Declarations

(PDT0) **PDT** ⟦ ε ⟧ (p)(vis)(u)(t) = u(t)

(PDT1) **PDT** ⟦ port-decl port-decl* ⟧ (p)(vis)(u)(t)
= **PDT** ⟦ port-decl ⟧ (p)(vis)(u_1)(t)
where u_1 = λt.**PDT** ⟦ port-decl* ⟧ (p)(vis)(u)(t)

The elaboration and checking of a sequence of port declarations proceeds from the first to the last declaration in the sequence.

(PDT2) **PDT** ⟦ **DEC PORT** id^+ mode type-mark opt-expr ⟧ (p)(vis)(u)(t)
= lookup-type(type-mark)(p)(z)(t)
where
z = λd.let type = (case mode
IN → mk-type(**(SIG VAL)**)(d),
OUT → mk-type(**(SIG OUT)**)(d),
(INOUT ,BUFFER) → mk-type(**(SIG REF)**)(d),
OTHERWISE
→ error
(cat("Illegal mode in port declaration: ")
(port-decl))) in
process-dec(id^+)(type)(opt-expr)(p)(vis)(u)(t)

Refer to the discussion following semantic equation **DT5** in Section 6.5.5.

(PDT3) **PDT** ⟦ **SLCDEC PORT** id^+ mode slice-name opt-expr ⟧ (p)(vis)(u)(t)
= let (type-mark,discrete-range) = slice-name in
lookup-type(type-mark)(p)(z)(t)
where
z = λd.let type = (case mode
IN → mk-type(**(SIG VAL)**)(d),
OUT → mk-type(**(SIG OUT)**)(d),
(INOUT ,BUFFER) → mk-type(**(SIG REF)**)(d),

```
                    OTHERWISE
                    → error
                          (cat("Illegal mode in port declaration: ")
                           (port-decl))) in
          process-slcdec
            (id+)(type)(discrete-range)(opt-expr)(p)(vis)(u)(t)
```

Refer to the discussion following semantic equation **DT6** in Section 6.5.5.

6.5.5 Declarations

(DT0) $\underline{\mathbf{DT}}$ ⟦ ε ⟧ (p)(vis)(u)(t) = u(t)

(DT1) $\underline{\mathbf{DT}}$ ⟦ decl decl* ⟧ (p)(vis)(u)(t)
= $\underline{\mathbf{DT}}$ ⟦ decl ⟧ (p)(vis)(u_1)(t)
where u_1 = λt.$\underline{\mathbf{DT}}$ ⟦ decl* ⟧ (p)(vis)(u)(t)

(DT2) $\underline{\mathbf{DT}}$ ⟦ pkg-decl pkg-decl* ⟧ (p)(vis)(u)(t)
= $\underline{\mathbf{DT}}$ ⟦ pkg-decl ⟧ (p)(vis)(u_1)(t)
where u_1 = λt.$\underline{\mathbf{DT}}$ ⟦ pkg-decl* ⟧ (p)(vis)(u)(t)

(DT3) $\underline{\mathbf{DT}}$ ⟦ pkg-body pkg-body* ⟧ (p)(vis)(u)(t)
= $\underline{\mathbf{DT}}$ ⟦ pkg-body ⟧ (p)(vis)(u_1)(t)
where u_1 = λt.$\underline{\mathbf{DT}}$ ⟦ pkg-body* ⟧ (p)(vis)(u)(t)

(DT4) $\underline{\mathbf{DT}}$ ⟦ use-clause use-clause* ⟧ (p)(vis)(u)(t)
= $\underline{\mathbf{DT}}$ ⟦ use-clause ⟧ (p)(vis)(u_1)(t)
where u_1 = λt.$\underline{\mathbf{DT}}$ ⟦ use-clause* ⟧ (p)(vis)(u)(t)

The elaboration and checking of a sequence of declarations proceeds from the first to the last declaration in the sequence.

```
(DT5) DT ⟦ DEC object-class id+ type-mark opt-expr ⟧ (p)(vis)(u)(t)
      = let q = find-progunit-env(t)(p) in
          let d = t(q)(*UNIT* ) in
           let tg = tag(d) in
            (case object-class
               (CONST ,SYSGEN ) → lookup-type(type-mark)(p)(z)(t),
               VAR
               → (case tg
                    (*PACKAGE* ,*ENTITY* ,*ARCHITECTURE* )
                    → error
                         (cat("Illegal VARIABLE declaration in ")(tg)(" context: ")
                          (decl)),
                    OTHERWISE → lookup-type(type-mark)(p)(z)(t)),
               SIG
               → (case tg
                    (*PROCESS* ,*PROCEDURE* ,*FUNCTION* )
                    → error
                         (cat("Illegal SIGNAL declaration in ")(tg)(" context: ")
                          (decl)),
                    OTHERWISE → lookup-type(type-mark)(p)(z)(t)),
               OTHERWISE → error
                                (cat("Illegal object class in declaration: ")(decl)))
          where
          z = λd.let type = (object-class = CONST → mk-type((CONST VAL) )(d),
                    mk-type(mk-tmode(object-class)(REF ))(d)) in
                process-dec(id+ )(type)(opt-expr)(p)(vis)(u)(t)
```

```
find-progunit-env(t)(p)
= (t(p)(*UNIT* )≠ *UNBOUND* → p,
   (null(p)→ error("No program unit ??! "),
    find-progunit-env(t)(rest(p))))

lookup-type(id*)(p)(z)(t)
= (null(id*)→ z(void-type-desc(t)),
   name-type(id*)(ε)(p)(t)(v)
    where
    v = λw.(second(tmode(w))= TYP → z(tdesc(w)),
          error(cat("Not a type: ")(namef(tdesc(w))))))

name-type(name)(w)(p)(t)(v)
= (null(w)
   → let w1 = lookup2(t)(p)(ε)(hd(name)) in
      (w1 = *UNBOUND* → error(cat("Unbound identifier: ")($(p)(hd(name)))),
       let tm = tmode(w1)
           and d = tdesc(w1) in
        (second(tm)∈ (OBJ TYP) → name-type(tl(name))(w1)(p)(t)(v),
         hd(tm)= PATH
         → (¬validate-access(name)(w1)(second(tm))
             → error(cat("Illegal access via: ")(namef(d))),
             name-type(tl(name))(((PATH ,tl(second(tm))),d))(p)(t)(v)),
         error
           (cat("Shouldn't happen in auxiliary semantic function NAME-TYPE: ")
            (w1)))),
   let d = tdesc(w) in
    let tg = tag(d) in
     (null(name)
      → (tg ∈ (*PROCEDURE* *FUNCTION*)
          → (null(pars(hd(signatures(d))))→ v(extract-rtype(d)),
             error(cat("Missing subprogram arguments: ")(namef(d)))),
          v(w)),
       let x = hd(name)
           and tm = tmode(w) in
        (consp(x)
         → (second(tm)= TYP
            → (null(tl(x))
               → name-type(tl(name))(((DUMMY ,VAL ),d))(p)(t)(v),
               error
                 (cat("Explicit conversion of multiple expressions to type: ")
                  (namef(d)))),
            list-type(x)(p)(t)(vv)
             where
             vv = λw1*.((second(tm)= OBJ ∧ is-array?(type(d)))
                                  ∨ (second(tm)∈ (REF VAL) ∧ is-array-tdesc?(d))
                  → (length(x)> 1
                     → error
                          (cat("Too many array indices for: ")(namef
                                                               (d))),
                     (is-integer-tdesc?(get-base-type(tdesc(hd(w1*))))
                      → name-type
                          (tl(name))
                          ((second(tm)= OBJ
                            → mk-type
                                (tmode(type(d)))(elty(tdesc(type(d)))),
                            mk-type(tm)(elty(d))))(p)(t)(v),
```

```
                    error
                      (cat("Non-integer array index for: ")(namef
                                                          (d))))),
                tg ∈ (*PROCEDURE* *FUNCTION*)
                → let rtype = compatible-signatures(w1*)(signatures(d)) in
                    (null(rtype)
                     → error
                          (cat("Incompatible parameter types for: ")
                           (namef(d))),
                      name-type(tl(name))(rtype)(p)(t)(v)),
                   error(cat("Cannot have an argument list: ")(namef
                                                          (d))))),
           ((second(tm)= OBJ ∧ is-record?(type(d)))
                 ∨ (second(tm)∈ (REF VAL) ∧ is-record-tdesc?(d))
            → let d1 = (second(tm)= OBJ → tdesc(type(d)), d) in
                let d2 = lookup-record-field(components(d1))(x) in
                 (d2 = *UNBOUND* → error(cat("Unknown record field: ")(x)),
                  let tmm = (second(tm)= OBJ → tmode(type(d)), tm) in
                   name-type(tl(name))(mk-type(tmm)(d2))(p)(t)(v)),
            second(tm)≠ OBJ ∨ second(tm)≠ TYP
            → let w1 = lookup-local(x)(%(path(d))(idf(d)))(p)(t) in
                (w1 = *UNBOUND*
                 → error(cat("Unknown identifier: ")($(%(path(d))(idf(d)))(x))),
                 second(tmode(w1))≠ ACC → name-type(tl(name))(w1)(p)(t)(v),
                 hd(tm)= PATH
                 → (¬null(tl(name))∧ ¬validate-access(name)(w1)(second(tm))
                     → error(cat("Illegal access via: ")(namef(tdesc(w1)))),
                     name-type
                       (tl(name))(((PATH ,tl(second(tm))),tdesc(w1)))(p)(t)
                       (v)),
                 error
                   (cat("Shouldn't happen in auxiliary semantic function NAME-TYPE: ")
                    (w1))),
            error(cat("Illegal access via: ")(namef(d)))))))

lookup2(t)(p)(q)(id)
= let d = t(p)(id) in
    (d = *UNBOUND*
     → (¬null(p)→ lookup2(t)(rest(p))(cons(last(p),q))(id), *UNBOUND* ),
     (case tag(d)
        (*OBJECT* ,*ENUMELT* ) → ((DUMMY ,OBJ ),d),
        (*PACKAGE* ,*PROCESS* ,*PROCEDURE* ,*FUNCTION* ,
         *LOOPNAME* ,*PROCESSNAME* )
        → ((PATH ,q),d),
        OTHERWISE → ((DUMMY ,TYP ),d)))

validate-access(name)(w)(q)
= let tg = tag(tdesc(w)) in
    (tg ∈ (*PROCEDURE* *FUNCTION*)
         ∧ (¬null(tl(name))∧ ¬consp(hd(tl(name))))
     → ¬null(q)∧ hd(name)= hd(q),
     tt)

list-type(expr*)(p)(t)(vv)
= (null(expr*)→ vv(ε),
    let expr = hd(expr*) in
     ET ⟦ expr ⟧ (p)(k)(t)
```

```
        where
        k = λ(w,e),t.
              (second(tmode(w))= ACC
               → error(cat("Non-value (an access): ")(namef(tdesc(w)))(expr)),
               list-type(tl(expr*))(p)(t)(λw*.vv(cons(w,w*)))))

lookup-local(id)(definition-path)(occurrence-path)(t)
= let d = t(definition-path)(id) in
    (d = *UNBOUND* → *UNBOUND* ,
     let tg = tag(d) in
      (tg ∈ (*LOOPNAME* *PROCESSNAME*) → ((DUMMY ,ACC ),d),
       (prefix-path(definition-path)(occurrence-path)∨ exported(d)
        → (case tg
             (*OBJECT* ,*ENUMELT* ) → ((DUMMY ,OBJ ),d),
             (*PACKAGE* ,*PROCESS* ,*PROCEDURE* ,*FUNCTION* ) → ((DUMMY ,ACC ),d),
             OTHERWISE → ((DUMMY ,TYP ),d)),
        *UNBOUND* )))

compatible-signatures(types)(signatures)
= (null(signatures)→ ε,
    let signature = hd(signatures) in
     (compatible-par-types(types)(extract-par-types(pars(signature)))
      → rtype(signature),
      compatible-signatures(types)(tl(signatures))))

compatible-par-types(actuals)(formals)
= (length(actuals)≠ length(formals)→ ff,
    length(actuals)= 0 → tt,
    let w1 = hd(actuals)
        and w2 = hd(formals) in
     (match-types(tdesc(w1),tdesc(w2))
      → let m1 = ref-mode(tmode(w1))
              and m2 = ref-mode(tmode(w2)) in
          (m1 = REF ∨ m1 = m2 → compatible-par-types(tl(actuals))(tl(formals)), ff),
      ff))

extract-par-types(pars)
= (null(pars)→ ε, cons(second(hd(pars)),extract-par-types(tl(pars))))

extract-rtype(d)
= let signature = hd(signatures(d)) in
    rtype(signature)

lookup-record-field(comp*)(id)
= (null(comp*)→ *UNBOUND* ,
    let (x,d) = hd(comp*) in
     (x = id → d, lookup-record-field(tl(comp*))(id)))

process-dec(id+)(w)(opt-expr)(p)(vis)(u)(t)
= (null(opt-expr)
    → (is-const?(w)→ error(cat("Uninitialized constant: ")($(p)(hd(id+)))),
       enter-objects(id+)(<ε,*OBJECT* ,p,vis,w,*UNDEF* ,ε>)(t)(p)(u)),
    let expr = opt-expr in
     RT ⟦ expr ⟧ (p)(k)(t)
     where
     k = λ(w1,e),t.
           let d = tdesc(w)
```

```
            and d1 = tdesc(w1) in
          (match-types(d,d1)
           → let init-val = ((is-sysgen?(w)∨ is-const?(w))
                                                ∧ ¬(is-array?(w)∨ is-record?(w))
                             → e,
                             *UNDEF* ) in
               enter-objects(id+)(<ε,*OBJECT* ,p,vis,w,init-val,ε>)(t)(p)(u),
             error(cat("Initialization type mismatch: ")(d)(d1))))

match-types(d1,d2)
= (case tag(d1)
     (*BOOL* ,*BIT* ,*REAL* ,*TIME* ,*ENUMTYPE* ) → d1 = get-base-type(d2),
     (*INT* ,*INT_TYPE* )
     → is-integer-tdesc?(get-base-type(d2))
          ∧ match-integer-types(d1)(get-base-type(d2)),
     *SUBTYPE* → match-types(get-base-type(d1),get-base-type(d2)),
     *ARRAYTYPE*
     → tag(d2)= *ARRAYTYPE* ∧ match-array-type-names(d1,d2),
     *RECORDTYPE*
     → tag(d2)= *RECORDTYPE*
          ∧ null(set-difference(filter-components(type(d1)))(filter-components(type(d2)))),
     OTHERWISE → match-type-names(idf(d1),idf(d2)))

match-integer-types(d1,d2)
= idf(d1)= UNIVERSAL_INTEGER ∨ idf(d2)= UNIVERSAL_INTEGER

get-base-type(d) = (tag(d)= *SUBTYPE* → base-type(d), d)

match-array-type-names(d1,d2)
= let idf1 = hd(d1)
        and idf2 = hd(d2) in
    (consp(idf1)∧ consp(idf2)→ match-type-names(hd(idf1),hd(idf2)),
     consp(idf1)→ match-type-names(hd(idf1),idf2),
     consp(idf2)→ match-type-names(idf1,hd(idf2)),
     match-type-names(idf1,idf2))

match-type-names(id1,id2)
= id1 = *ANONYMOUS* ∨ id2 = *ANONYMOUS*

array-size(d)
= (ub(d)∧ lb(d)
   → let lbound = hd(tl(lb(d)))
          and ubound = hd(tl(ub(d))) in
       (ubound−lbound)+1,
   -1)

filter-components(components)
= (null(components)→ ε,
   let component = hd(components) in
    cons((hd(component),second(component)),
    filter-components(tl(components))))
```

An object declaration declares a *list* of identifiers to be of the type given by the type-mark, which must be the name of a type that has already been entered in the visible part of the TSE. The identifiers must be distinct. The first of these identifiers is used in error messages.

If the identifiers are being declared as constants but no initialization expression is present, then an UNINITIALIZED-CONSTANT error is reported. If constants are being declared, then their type is a *value type*; variables and signals have *reference types*. If variables or signals are being declared without an initialization expression, then the identifiers are entered into the TSE with an undefined initial value ***UNDEF*** by the function **enter-objects**, whose operation is explained below. If present, the initialization expression is checked and its type compared to the value type of the declared identifiers. If these types are not equal, then an initialization type mismatch is reported. If the identifiers are being declared as constants, they are entered into the TSE with an initial value equal to the (static) value of the initialization expression.

The function **enter-objects** enters into the TSE a scalar descriptor for each of a *list* of identifiers. Duplicate declarations are detected. The descriptors are created from (1) the identifiers and (2) a list of remaining field values input to **enter-objects**.

The function **name-type** returns the type (consisting of a type *mode* and a type *descriptor*) of a *reference* (**ref**). In Phase 1, **ref**s are essentially sequences of identifiers and expression lists; **ref**s must begin with an identifier. As **name-type** processes a **ref**, it carries along (in parameters **name** and **w**, respectively) the remainder of the **ref** to be processed and the type to be computed for that portion of the original **ref** processed thus far. During this processing, special type modes that are identifier lists may be used to validate accesses to items declared inside packages or subprograms; **validate-access** checks these accesses. The function **list-type** returns the list of the types of its components; when a list is used as an actual parameter list in a subprogram call, **compatible-par-types** checks whether the types of this list's components are compatible with (not necessarily equal to) the types of the corresponding formal parameters of the subprogram.

```
(DT6) DT [[ SLCDEC object-class id+ slice-name opt-expr ]] (p)(vis)(u)(t)
      = let (type-mark,discrete-range) = slice-name in
          let q = find-progunit-env(t)(p) in
           let d = t(q)(*UNIT* ) in
            let tg = tag(d) in
             (case object-class
                (CONST ,SYSGEN ) → lookup-type(type-mark)(p)(z)(t),
                VAR
                → (case tg
                     (*PACKAGE* ,*ENTITY* ,*ARCHITECTURE* )
                     → error
                          (cat("Illegal VARIABLE declaration in ")(tg)
                           (" context: ")(decl)),
                     OTHERWISE → lookup-type(type-mark)(p)(z)(t)),
                SIG
                → (case tg
                     (*PROCESS* ,*PROCEDURE* ,*FUNCTION* )
                     → error
                          (cat("Illegal SIGNAL declaration in ")(tg)(" context: ")
                           (decl)),
                     OTHERWISE → lookup-type(type-mark)(p)(z)(t)),
                OTHERWISE
                → error(cat("Illegal object class in declaration: ")(decl)))
           where
           z = λd.let type = (object-class = CONST → mk-type((CONST VAL) )(d),
```

```
                    mk-type(mk-tmode(object-class)(REF ))(d)) in
                process-slcdec(id+)(type)(discrete-range)(opt-expr)(p)(vis)(u)(t)

process-slcdec(id+)(w)(discrete-range)(opt-expr)(p)(vis)(u)(t)
= let d = tdesc(w) in
   (¬is-array?(w)→ error(cat("Can't form slice of non-array type: ")(d)),
    let (direction,expr1,expr2) = discrete-range in
     RT ⟦ expr1 ⟧ (p)(k1)(t)
      where
      k1 = λ(w1,e1),t.
            RT ⟦ expr2 ⟧ (p)(k2)(t)
             where
             k2 = λ(w2,e2),t.
                   (¬(is-integer-tdesc?(get-base-type(tdesc(w1)))
                                  ∧ is-integer-tdesc?(get-base-type(tdesc(w2))))
                   → error
                        (cat("Non-integer array bound for: ")($(p)
                                                    (hd(id+)))),
                   let field-values = tl(array-type-desc
                                         (TEMP_NAME )(ε)(p)(vis)
                                         (direction)
                                         ((direction = TO
                                           → (e1 = *UNDEF*
                                              → second(EX ⟦ expr1 ⟧ (p)(t)),
                                              (NUM ,e1)),
                                           (e2 = *UNDEF*
                                            → second(EX ⟦ expr2 ⟧ (p)(t)),
                                            (NUM ,e2))))
                                         ((direction = TO
                                           → (e2 = *UNDEF*
                                              → second(EX ⟦ expr2 ⟧ (p)(t)),
                                              (NUM ,e2)),
                                           (e1 = *UNDEF*
                                            → second(EX ⟦ expr1 ⟧ (p)(t)),
                                            (NUM ,e1))))(elty(d))) in
                    (null(opt-expr)
                     → enter-array-objects
                          (id+)(idf(d))(tmode(w))(field-values)(t)(p)(vis)
                          (u),
                     check-array-aggregate(opt-expr)(p)(v)(t)
                      where
                      v = λw3.(match-types(elty(d),tdesc(w3))
                            → enter-array-objects
                                 (id+)(idf(d))(tmode(w))
                                 (field-values)(t)(p)(vis)(u),
                            error
                               (cat("Initialization type mismatch for: ")
                                ($(p)(hd(id+)))))))))

enter-array-objects(id*)(array-type-name)(tmode)(field-values)(t)(p)(vis)(u)
= (null(id*)→ u(t),
   let id1 = hd(id*) in
    let id2 = new-array-type-name(array-type-name) in
     let d1 = cons(id2,field-values) in
      let t1 = enter(t)(p)(id2)(field-values) in
       let new-type = mk-type(tmode)(d1) in
        (t(p)(id1)≠ *UNBOUND*
```

```
        → error(cat("Duplicate array declaration: ")($(p)(id1))),
        let d2 = <ε,*OBJECT* ,p,vis,new-type,*UNDEF* ,ε> in
         let t2 = enter(t1)(p)(id1)(d2) in
          enter-array-objects
            (tl(id*))(array-type-name)(tmode)(field-values)(t2)(p)(vis)(u)))

check-array-aggregate(expr)(p)(v)(t)
= let (tg,expr+) = expr in
   (tg ≠ BITSTR ∧ tg ≠ STR
    → error(cat("Improper array initialization aggregate: ")(expr)),
    let expr1 = hd(expr+) in
     RT [[ expr1 ]] (p)(k)(t)
      where k = λ(w1,e1),t.check-exprs(w1)(tl(expr+))(p)(v)(t))

check-exprs(w)(expr*)(p)(v)(t)
= (null(expr*)→ v(w),
   let expr = hd(expr*) in
    RT [[ expr ]] (p)(k)(t)
     where
     k = λ(w1,e1),t.
          (w1 ≠ w → "Nonuniform array aggregate ",
           check-exprs(w)(tl(expr*))(p)(v)(t)))
```

A declaration of a slice of a (previously defined) array type is a special form of object declaration for arrays of *anonymous* type. Because a declaration of a list of identifiers is considered to be an abbreviated representation of the sequence of corresponding declarations of each of the individual identifiers in the list, the (anonymous) type of each of the declared identifiers is *distinct.* Each of these distinct anonymous array types is given a distinct, new, system-generated name in Phase 1 of the Stage 3 VHDL translator (via the function **new-array-type-name**), and corresponding distinct type descriptors are entered into the TSE. If present, the initialization part of the declaration is a *list* of scalar expressions.

The elaboration and checking of a slice declaration begins in the same way as for a scalar declaration. The slice bound expressions are then evaluated and checked to ensure that both are integers. If the initialization part is absent, then descriptors for the declared array identifiers, together with the descriptors for the corresponding anonymous array types, are entered into the environment by **enter-array-objects**.

If the initialization part is present, then it is first processed by **check-array-aggregate**, which invokes **check-exprs** to ensure that each element of the initialization part has the same (value) type; **check-aggregate** returns this type, which is then compared to the array's declared value type. Finally, **enter-array-objects** is invoked to enter the descriptors for the declared arrays into the environment.

Refer also semantic equation **DT8**, shown below.

```
(DT7) DT [[ ETDEC id id+ ]] (p)(vis)(u)(t)
      = let field-values1 = <ε,*ENUMTYPE* ,p,vis,mk-enumlit(hd(id+)),
                            mk-enumlit(last(id+)),id+> in
         (check-enum-lits(t)(p)(id)(id+)
          → enter-objects((id))(field-values1)(t)(p)(u1),
          nil)
           where
```

```
        u1 = λt1.let d = cons(id,field-values1) in
                let field-values2 = <ε,*ENUMELT* ,p,vis,
                                    mk-type((CONST VAL) )(d)> in
                 enter-objects(id+)(field-values2)(t1)(p)(u)

check-enum-lits(t)(p)(id)(id*)
= (null(id*)→ tt,
   let id1 = hd(id*) in
    (lookup(t)(p)(id1)= *UNBOUND* → check-enum-lits(t)(p)(id)(tl(id*)),
     error
       (cat("Illegal overloading for enumeration literal: ")(id1)
        (" in enumeration type: ")($(p)(id)))))
```

An enumeration type declaration causes corresponding enumeration type descriptors to be entered into the TSE. At the same time, descriptors for the individual elements of the enumeration type are entered into the TSE; these elements are treated as constants.

```
(DT8) DT [[ ATDEC id discrete-range type-mark ]] (p)(vis)(u)(t)
      = lookup-type(type-mark)(p)(z)(t)
          where
          z = λd.let (direction,expr1,expr2) = discrete-range in
                 let array-type-desc = array-type-desc
                                       (id)(ε)(p)(vis)(direction)
                                       ((direction = TO
                                         → second(EX [[ expr1 ]] (p)(t)),
                                         second(EX [[ expr2 ]] (p)(t))))
                                       ((direction = TO
                                         → second(EX [[ expr2 ]] (p)(t)),
                                         second(EX [[ expr1 ]] (p)(t))))(d) in
                  attributes-low-high
                    ((id,expr1,expr2,array-type-desc,(UNIVERSAL_INTEGER) ))(p)
                    (vis)(u)(t)

attributes-low-high(id,expr1,expr2,type-desc,attribute-type-mark)(p)(vis)(u)(t)
= let decl1 = (DEC ,SYSGEN ,(mk-tick-low(id)),attribute-type-mark,expr1)
      and decl2 = (DEC ,SYSGEN ,(mk-tick-high(id)),attribute-type-mark,expr2) in
    enter-objects((id))(tl(type-desc))(t)(p)(u1)
     where u1 = λt1.DT [[ decl1 ]] (p)(vis)(u2)(t1)
     where u2 = λt2.DT [[ decl2 ]] (p)(vis)(u)(t2)

mk-tick-low(id) = catenate(id,"'LOW")

mk-tick-high(id) = catenate(id,"'HIGH")
```

An array type declaration causes corresponding array type descriptors to be entered into the TSE. The array type attributes `'low` and `'high`, representing the lower and upper bounds, respectively, are declared as system-generated identifiers.

```
(DT9) DT [[ PACKAGE id decl* opt-id ]] (p)(vis)(u)(t)
      = (t(p)(id)≠ *UNBOUND*
          → error(cat("Duplicate package declaration: ")($(p)(id))),
          (¬null(opt-id)∧ opt-id ≠ id
           → error
                (cat("Package ")($(p)(id))(" ended with incorrect identifier: ")
```

```
        (opt-id)),
    let d = <ε,*PACKAGE* ,p,vis,ε> in
     let t1 = enter(t)(p)(id)(d) in
      let t2 = enter(extend(t1)(p)(id))(%(p)(id))(*UNIT* )(<ε,*PACKAGE* >) in
       let t3 = enter(t2)(%(p)(id))(*USED* )(<ε,ε>) in
        let t4 = enter(t3)(%(p)(id))(*IMPT* )(<ε,ε,ε>) in
         u1(t4)
        where u1 = λt.DT [[ decl* ]] (%(p)(id))(tt)(u)(t)))

(DT10) DT [[ PACKAGEBODY id decl* opt-id ]] (p)(vis)(u)(t)
     = let d = t(p)(id) in
       (d = *UNBOUND* → error(cat("Missing package declaration: ")($(p)
                                                                  (id))),
        tag(d)≠ *PACKAGE* → error(cat("Not a package declaration: ")($(p)
                                                                  (id))),
        ¬null(pbody(d))→ error(cat("Duplicate package body: ")($(p)(id))),
        ¬null(opt-id)∧ opt-id ≠ id
        → error
            (cat("Package body ")($(p)(id))(" ended with incorrect identifier: ")
             (opt-id)),
        let q = %(path(d))(id) in
         let t1 = enter(t)(q)(*LAB* )(<ε,ε>) in
          let t2 = enter(t1)(p)(id)(<ε,*PACKAGE* ,path(d),exported(d),*BODY* >) in
           DT [[ decl* ]] (q)(ff)(u)(t2))
```

A package is an encapsulated collection of declarations (including other packages) of logically related entities identified by the package's name. A package is generally provided in two parts: the *package declaration* and the *package body*. The package declaration provides declarations of those items that are *exported* (i.e., made visible) by the package. The package body provides the bodies of items whose declarations appear in the package declaration, together with the declarations and bodies of additional items that support the items exported by the package. These latter items are not exported by the package, i.e., they cannot be made visible outside the package. In our implementation, the descriptors of exported and nonexported items alike are entered into the same local environment. The *exported* field of these descriptors distinguishes between the two kinds of items. If an item can be exported by a USE clause, then the *exported* field of its descriptor contains **tt** (denoting **true**; if not, then this field contains **ff** (**false**).

The items declared in a package declaration are not directly visible outside the package, but they can be accessed by using a dotted name beginning with the package name, provided that the package name is visible at the point of access. A descriptor for the package declaration is entered into the current environment. In order to encapsulate the items within a package, the resulting TSE is then extended along the current path by an edge labeled with the package name; the new environment is marked (in its ***UNIT*** cell) as a package environment. Then the constituent declarations of the package are elaborated and checked in the new environment.

The items declared in a package body are not exported from the package and thus must not be accessible by an extended name. Therefore the *exported* field of the descriptors for the inaccessible entities must be set to **ff**, thus marking them as *not exportable*.

(DT11) DT [[**PROCEDURE** id proc-par-spec*]] (p)(vis)(u)(t)

```
      = (t(p)(id)≠ *UNBOUND*
         → error(cat("Duplicate procedure declaration for: ")($(p)(id))),
         let p1 = %(p)(id) in
          let t1 = enter(extend(t)(p)(id))(p1)(*UNIT* )(<ε,*PROCEDURE* >) in
           enter-formal-pars(*PROCEDURE* )(proc-par-spec*)(t1)(p1)(u1)
            where
            u1 = λt2.let formals = let id+ = collect-fids(proc-par-spec*) in
                                   collect-formal-pars(id+)(t2)(p1) in
                 let d = <ε,*PROCEDURE* ,p,vis,
                          ((formals,
                            mk-type((CONST VAL) )(void-type-desc(t)))),ε,ε> in
                  u(enter(t2)(p)(id)(d)))

(DT12) DT [[ FUNCTION id func-par-spec* type-mark ]] (p)(vis)(u)(t)
      = (t(p)(id)≠ *UNBOUND*
         → error(cat("Duplicate function declaration for: ")($(p)(id))),
         let p1 = %(p)(id) in
          lookup-type(type-mark)(p)(z)(t)
           where
           z = λd1.let t1 = enter
                            (extend(t)(p)(id))(p1)(*UNIT* )(<ε,*FUNCTION* >) in
                enter-formal-pars(*FUNCTION* )(func-par-spec*)(t1)(p1)(u1)
                 where
                 u1 = λt2.let formals = let id+ = collect-fids
                                                  (func-par-spec*) in
                                        collect-formal-pars
                                          (id+)(t2)(p1) in
                      let d = <ε,*FUNCTION* ,p,vis,
                               ((formals,mk-type((VAR VAL) )(d1))),ε,ε> in
                       u(enter(t2)(p)(id)(d)))

enter-formal-pars(tg)(par-spec*)(t)(p)(u)
= (null(par-spec*)→ u(t),
   let par-spec = hd(par-spec*) in
    let (object-class,id+,mode,type-mark,opt-expr) = par-spec in
     (case tg
       *PROCEDURE*
       → (case object-class
            (CONST ,VAR )
            → (case mode
                 (IN ,OUT ,INOUT ) → lookup-type(type-mark)(p)(z)(t),
                 OTHERWISE
                 → error
                      (cat("Illegal mode for procedure parameters: ")($(p)
                                                                  (hd(id+))))),
            OTHERWISE
            → error
                 (cat("Unimplemented object class ")(object-class)
                  (" for procedure parameters: ")($(p)(hd(id+))))),
       *FUNCTION*
       → (case object-class
            CONST
            → (case mode
                 IN → lookup-type(type-mark)(p)(z)(t),
                 OTHERWISE
                 → error
                      (cat("Illegal mode for function parameters: ")($(p)
```

```
                                                              (hd(id+))))),
          OTHERWISE
          → error
               (cat("Unimplemented object class ")(object-class)
                (" for function parameters: ")($(p)(hd(id+)))))),
      OTHERWISE → error(cat("Illegal subprogram tag: ")(tg)))
    where
    z = λd.let type = (case mode
                         IN → mk-type(mk-tmode(object-class)(VAL ))(d),
                         OUT → mk-type(mk-tmode(object-class)(OUT ))(d),
                         OTHERWISE → mk-type(mk-tmode(object-class)(REF ))(d)) in
          let fv = <ε,*OBJECT* ,p,tt,type,*UNDEF* ,ε> in
           enter-objects(id+)(fv)(t)(p)(u1)
            where u1 = λt.enter-formal-pars(tg)(tl(par-spec*))(t)(p)(u))

collect-fids(par-spec*)
= (null(par-spec*)→ ε,
   let par-spec = hd(par-spec*) in
    let (object-class,id+,mode,type-mark,opt-expr) = par-spec in
     append(id+,collect-fids(tl(par-spec*))))

collect-formal-pars(id*)(t)(p)
= (null(id*)→ ε,
   let d = t(p)(hd(id*)) in
    cons((hd(id*),type(d)),collect-formal-pars(tl(id*))(t)(p)))
```

Checking a subprogram (procedure or function) declaration first extends the TSE and identifies the new environment at the end of the extended path (in its ***UNIT*** cell) as a procedure or function environment. Then descriptors for the subprogram's formal parameters are entered (by **enter-formal-pars**) into this new environment. Finally, a descriptor for the subprogram (with a **body** field of **ff**, indicating that no body for this subprogram has been encountered) is entered into the environment in which the subprogram is declared locally. Procedures are always given a *void* return type. The function **enter-formal-pars** accepts a tag ***PROCEDURE*** or ***FUNCTION*** (procedure or function) to enable it to check that the formal parameters are appropriate to the subprogram. For example, functions can have only `IN` parameters.

```
(DT13) DT ⟦ SUBPROGBODY subprog-spec decl* seq-stat* opt-id ⟧ (p)(vis)(u)(t)
       = let (tg,id,par-spec*,type-mark) = subprog-spec in
          let qname = $(p)(id)
              and d = t(p)(id) in
           (d = *UNBOUND*
            → let decl = subprog-spec in
                DT ⟦ decl ⟧ (p)(vis)(u1)(t)
                where
                u1 = λt.let d = t(p)(id) in
                         process-subprog-body
                           (t)(p)(id)(d)(decl*)(seq-stat*)(u),
               ¬(tag(d)∈ (*PROCEDURE* *FUNCTION*) )
               → error(cat(qname)(" is not a subprogram specification")),
               (tg = PROCEDURE ∧ tag(d)= *FUNCTION* )
                        ∨ (tg = FUNCTION ∧ tag(d)= *PROCEDURE* )
               → error(cat("Wrong kind of subprogram body: ")(qname)),
               ¬null(body(d))→ error(cat("Duplicate subprogram body: ")(qname)),
```

```
        ¬null(opt-id)∧ opt-id ≠ id
        → error
              (cat("Subprogram body ")(qname)
               (" ended with incorrect identifier ")(opt-id)),
        let formals = let id+ = collect-fids(par-spec*) in
                      collect-formal-pars(id+)(t)(%(p)(id)) in
         (formals ≠ pars(hd(signatures(d)))
          → error
               (cat("Nonconforming formal parameters for subprogram: ")(qname)),
          lookup-type(type-mark)(p)(z)(t)
           where
           z = λd1.(d1 ≠ tdesc(extract-rtype(d))
                → error
                     (cat("Unequal result types for subprogram: ")
                      (qname)),
                process-subprog-body(t)(p)(id)(d)(decl*)(seq-stat*)(u))))

process-subprog-body(t)(p)(id)(d)(decl*)(seq-stat*)(u)
= let p1 = %(p)(id) in
   let t1 = enter(t)(p1)(*LAB* )((ε,ε)) in
    let t5 = enter(t1)(p1)(*USED* )(<ε,ε>) in
     let t6 = enter(t5)(p1)(*IMPT* )(<ε,ε,ε>) in
      let t7 = enter
                 (t6)(p)(id)(<ε,tag(d),path(d),exported(d),signatures(d),ε,ε>) in
       DT [[ decl* ]] (p1)(tt)(u1)(t7)
        where u1 = λt2.SST [[ seq-stat* ]] (p1)(u2)(t2)
        where
        u2 = λt3.let t4 = enter
                          (t3)(p)(id)
                          (<ε,tag(d),path(d),exported(d),signatures(d),
                            (DX [[ decl* ]] (p1)(t3),SSX [[ seq-stat* ]] (p1)(t3)),ε>) in
             u(t4)
```

Checking the declaration of a *subprogram body* first checks whether a declaration for the subprogram has already been encountered. If not, then descriptors for the subprogram and its formal parameters must be entered into the TSE as above. Otherwise, the declaration part of the subprogram body must be checked for conformity with the corresponding information previously entered in the TSE. In Stage 3 VHDL conformity is very strict: subprogram types and formal parameter names and types must agree *exactly*, except that formal parameters with no explicit mode are regarded as having been specified with mode `IN`. The subprogram's body (which consists of local declarations followed by statements) is checked by **process-subprog-body**, where initial entries are made into its environment's ***LAB***, ***USED***, and ***IMPT*** cells, and its *transformed* abstract syntax tree is entered into the *body* field of the subprogram's descriptor. Note that a dummy value ***BODY*** is temporarily entered in the descriptor's **body** field, so that recursive calls of this subprogram will not incorrectly indicate that a call is being made to a subprogram for which a body has not been supplied (see the Phase 1 semantics of subprogram calls).

```
(DT14) DT [[ USE dotted-name+ ]] (p)(vis)(u)(t)
       = let pkgs-used-here = tl(dotted-name+)∪ {hd(dotted-name+)} in
           process-use-clause(pkgs-used-here)(p)(vis)(u)(t)

process-use-clause(dotted-name+)(p)(vis)(u)(t)
```

```
= check-pkg-names(dotted-name+)(ε)(p)(vis)(j)(t)
    where
    j = λpkg-qualified-names.
          let pkg-qnames = remove-enclosing-pkgs(p)(t)(pkg-qualified-names) in
           let local-pkgs-used = third(t(p)(*USED* )) in
            let t1 = enter
                        (t)(p)(*USED* )
                        ((ε,pkg-qnames ∪ local-pkgs-used)) in
             let t2 = let d = t(p)(*IMPT* ) in
                        let qname-list = third(d)
                            and id-list = fourth(d) in
                         import-qualified-names
                            (pkg-qnames)(qname-list)(id-list)(p)(t1 ) in
              u(t2)

check-pkg-names(dotted-name*)(pkg-qualified-names)(p)(vis)(j)(t)
= (null(dotted-name*)→ j(pkg-qualified-names),
    let dn = hd(dotted-name*) in
     let suffix = last(dn) in
      (suffix ≠ ALL
       → error(cat("Selected name in USE clause must end with suffix ALL: ")(dn)),
       name-type(rest(dn))(ε)(p)(t)(v)
        where
        v = λw.let d = tdesc(w) in
              (tag(d)≠ *PACKAGE*
               → error(cat("Non-package name in USE clause: ")(namef
                                                                  (d))),
               check-pkg-names
                  (tl(dotted-name*))(cons(%(path(d))(idf(d)),pkg-qualified-names))
                  (p)(vis)(j)(t))))

remove-enclosing-pkgs(p)(t)(pkg-set)
= (null(p)→ pkg-set,
    let d = t(p)(*UNIT* ) in
     (d = *UNBOUND* → remove-enclosing-pkgs(rest(p))(t)(pkg-set),
      (third(d)= *PACKAGE*
       → remove-enclosing-pkgs(rest(p))(t)(set-difference(pkg-set)((p))),
       remove-enclosing-pkgs(rest(p))(t)(pkg-set))))

import-qualified-names(pkg-qualified-names)(item-qualified-names)(ids-used)(p)(t)
= (pkg-qualified-names = ε
   → enter(t)(p)(*IMPT* )((ε,item-qualified-names,ids-used)),
   let pkg-qn = hd(pkg-qualified-names) in
    let pkg-env = t(pkg-qn) in
     let exported-qnames = export-qualified-names(pkg-env)(ε) in
      let local-env = t(p) in
       let (qname*,id*) = import-legal
                             (exported-qnames)(item-qualified-names)(ids-used)
                             (local-env) in
            import-qualified-names(tl(pkg-qualified-names))(qname*)(id*)(p)(t))

import-legal(exported-qnames)(qname-list)(id-list)(env)
= (null(exported-qnames)→ (qname-list,id-list),
    let qname = hd(exported-qnames) in
     let id = last(qname) in
      let remaining-exported-qnames = tl(exported-qnames) in
       (id ∈ id-list
```

```
        → let qn = simple-name-match(id)(qname-list) in
            (null(qn)
             → import-legal(remaining-exported-qnames)(qname-list)(id-list)(env),
             import-legal
                (remaining-exported-qnames)(set-difference(qname-list)((qn)))
                (id-list)(env)),
          let d = env(id) in
           (d = *UNBOUND*
            → import-legal
                (remaining-exported-qnames)(cons(qname,qname-list))
                (cons(id,id-list))(env),
            import-legal
              (remaining-exported-qnames)(qname-list)(cons(id,id-list))(env))))

simple-name-match(id)(qname*)
= (null(qname*)→ ε,
   (id = last(hd(qname*))→ hd(qname*), simple-name-match(id)(tl(qname*))))

export-qualified-names(env)(qualified-names)
= (null(env)→ qualified-names,
   let d = hd(env) in
    let id = idf(d) in
     (case id
        (*UNIT* ,*LAB* ,*USED* ,*IMPT* )
        → export-qualified-names(tl(env))(qualified-names),
        OTHERWISE
        → (exported(d)
            → export-qualified-names(tl(env))(cons(%(path(d))(id),qualified-names)),
            export-qualified-names(tl(env))(qualified-names))))
```

A USE clause is a declaration that makes items declared in a package specification visible at the location of the USE clause. Each of the dotted names in a USE clause, neglecting the (obligatory) suffix ALL, must denote the name of a package. In essence, a USE clause combines the exported environments associated with its named packages both with each other and with the local environment (among whose declarations the USE clause appears). Such a combination of environments may introduce conflicts, since there may be several different declarations of an object of the same name in the packages (as well as one locally). Therefore, certain constraints must govern how environments are combined:

1. If an object **x** is declared locally, then *no* declarations of **x** may be imported to the local environment by the USE clause.

2. If an object **x** is declared in more than one of the packages named in the USE clause, then *none* of these declarations of **x** may be imported to the local environment by the USE clause, even if **x** is not declared locally.

These constraints ensure that (1) no local declaration is masked by an imported one, and (2) no duplicate or conflicting declarations are imported.

USE clauses are treated by **process-use-clause**, which assumes that all the USE clauses in a program unit's declarative part are located together at the *end* of that declarative part.

This restriction on the location and grouping of USE clauses enables a determination of those items imported into a local environment to be made *once and for all by the time the unit's declarative part has been processed.* This ensures that the list of items imported into an environment (stored in its ***IMPT*** cell) need not vary in Phase 2, thereby ensuring that the entire TSE is *fixed* throughout Phase 2. If declarations other than USE clauses were allowed to appear between USE clauses, then the set of importable items may change before and after such interposed declarations, requiring a dynamic evaluation of the import list during Phase 2. We feel that such generality is unnecessary, because the names of items can always be changed so that their interposed declarations can be moved in front of the group of USE clauses.

First, the list of names appearing in this USE clause (with duplicates removed) is given to **process-use-clause.** Then these names are checked by **check-pkg-names** to ensure that they denote packages; a list of fully qualified package names is returned. The names of packages that enclose packages in this list are removed by **remove-enclosing-packages.** The (set-theoretic) union of the resulting set of package names (called **pkg-qnames**) and the set of names of packages already appearing in USE clauses in this declarative part (stored in the ***USED*** cell of this environment) is computed (in order to avoid duplication); the resulting set of package names is entered back into the ***USED*** cell. Next, the current set of fully qualified names of items imported into this environment (**qname-list**) is retrieved from its ***IMPT*** cell. A separate list of simple identifiers (**id-list**) is also maintained in the ***IMPT*** cell; this list is used to prevent illegal importations into the current environment. Then **pkg-qnames**, **qname-list**, and **id-list** are passed to **import-qualified-names**, which adds the fully qualified names of those items that can be legally imported into the local environment by the USE clause being processed. The auxiliary functions **export-qualified-names** and **import-legal** are used by **import-qualified-names.**

```
(DT15) DT [[ STDEC id type-mark opt-discrete-range ]] (p)(vis)(u)(t)
       = lookup-type(type-mark)(p)(z)(t)
          where
          z = λd.let base-type-desc = get-base-type(d) in
                (null(opt-discrete-range)
                 → let field-values = <ε,*SUBTYPE* ,p,vis,type-tick-low(d),
                                       type-tick-high(d),base-type-desc> in
                    attributes((id,ε,ε,d,field-values))(p)(vis)(u)(t),
                 let (direction,expr1,expr2) = opt-discrete-range in
                  RT [[ expr1 ]] (p)(k1)(t)
                   where
                   k1 = λ(w1,e1),t.
                         RT [[ expr2 ]] (p)(k2)(t)
                          where
                          k2 = λ(w2,e2),t.
                                (match-types(tdesc(w1),base-type-desc)
                                ∧ match-types(tdesc(w2),base-type-desc)
                                  → let field-values = <ε,*SUBTYPE* ,p,vis,
                                                        (direction = TO
                                                         → (e1 = *UNDEF*
                                                            → second
                                                                 (EX [[ expr1 ]]
                                                                      (p)(t)),
                                                            (NUM ,e1)),
                                                        (e2 = *UNDEF*
```

```
                                        → second
                                            (EX ⟦ expr2 ⟧
                                                (p)(t)),
                                         (NUM ,e2))),
                                        (direction = TO
                                        → (e2 = *UNDEF*
                                            → second
                                                (EX ⟦ expr2 ⟧
                                                    (p)(t)),
                                            (NUM ,e2)),
                                         (e1 = *UNDEF*
                                         → second
                                             (EX ⟦ expr1 ⟧
                                                 (p)(t)),
                                          (NUM ,e1))),base-type-desc> in
                    attributes
                       ((id,
                         (direction = TO → expr1,
                          expr2),
                         (direction = TO → expr2,
                          expr1),d,field-values))(p)
                        (vis)(u)(t),
                error
                   (cat("Range constraint for subtype incompatible with base type: ")
                    (base-type-desc)(tdesc(w1))
                    (tdesc(w2))(decl))))

attributes(id,lower-bound,upper-bound,d,field-values)(p)(vis)(u)(t)
= let decl1 = (DEC ,SYSGEN ,(mk-tick-low(id)),(idf(d)),lower-bound)
      and decl2 = (DEC ,SYSGEN ,(mk-tick-high(id)),(idf(d)),upper-bound) in
    enter-objects((id))(field-values)(t)(p)(u1)
     where u1 = λt1.DT ⟦ decl1 ⟧ (p)(vis)(u2)(t1)
     where u2 = λt2.DT ⟦ decl2 ⟧ (p)(vis)(u)(t2)
```

Static semantic analysis of a subtype declaration involves making certain that the lower and upper bounds of the range constraint are compatible with the subtype's base type; declaring the `'low` and `'high` attributes (representing these bounds) as system-generated identifiers; and entering a subtype descriptor in the TSE.

```
(DT16) DT ⟦ ITDEC id discrete-range ⟧ (p)(vis)(u)(t)
       = let parent-type-desc = univint-type-desc(t) in
           let (direction,expr1,expr2) = discrete-range in
            RT ⟦ expr1 ⟧ (p)(k1)(t)
             where
             k1 = λ(w1,e1),t.
                    RT ⟦ expr2 ⟧ (p)(k2)(t)
                     where
                     k2 = λ(w2,e2),t.
                            (e1 = *UNDEF* ∨ e2 = *UNDEF*
                             → error
                                  (cat("Non-static bound in range constraint: ")
                                   (decl)),
                             (match-types(tdesc(w1),parent-type-desc)
                                                ∧ match-types(tdesc(w2),parent-type-desc)
                              → let field-values = <ε,*INT_TYPE* ,p,vis,
```

```
                                    (direction = TO
                                     → (NUM ,e1),
                                     (NUM ,e2)),
                                    (direction = TO
                                     → (NUM ,e2),
                                     (NUM ,e1)),parent-type-desc> in
          attributes
             ((id,(direction = TO → expr1, expr2),
               (direction = TO → expr2, expr1),parent-type-desc,field-values))
             (p)(vis)(u)(t),
       error
          (cat("Incompatible range constraint for integer type: ")
           (tdesc(w1))(tdesc(w2))(decl))))
```

Static semantic analysis of an integer definition type involves making certain that the lower and upper bounds of the range constraint are static expressions compatible with the integer type's parent type (`UNIVERSAL_INTEGER`); declaring the `'low` and `'high` attributes (representing these bounds) as system-generated identifiers; and entering an integer definition type descriptor in the TSE.

6.5.6 Concurrent Statements

(CST0) $\underline{\mathbf{CST}}\ [\![\ \varepsilon\ ]\!]\ (p)(u)(t) = u(t)$

(CST1) $\underline{\mathbf{CST}}\ [\![\ \text{con-stat con-stat}^*\ ]\!]\ (p)(u)(t)$
$= \underline{\mathbf{CST}}\ [\![\ \text{con-stat}\ ]\!]\ (p)(u_1)(t)$
where $u_1 = \lambda t.\underline{\mathbf{CST}}\ [\![\ \text{con-stat}^*\ ]\!]\ (p)(u)(t)$

Concurrent statements are statically checked in the textual order of their appearance in the hardware description.

(CST2) $\underline{\mathbf{CST}}\ [\![\ \mathbf{PROCESS}\ \text{id ref}^*\ \text{decl}^*\ \text{seq-stat}^*\ \text{opt-id}\ ]\!]\ (p)(u)(t)$
$=$ **let** $q = \text{find-architecture-env}(t)(p)$ **in**
let $\text{labels} = \text{third}(t(q)(\mathbf{*LAB*}))$ **in**
$(\text{id} \in \text{labels} \rightarrow \text{error}(\text{cat}(\text{"Duplicate process label: "})(\$(q)(\text{id}))),$
let $t_1 = \text{enter}(t)(q)(\mathbf{*LAB*})((\varepsilon,\text{cons}(\text{id},\text{labels})))$ **in**
$(\neg\text{null}(\text{opt-id}) \wedge \text{opt-id} \neq \text{id}$
$\rightarrow$ error
(cat("PROCESS statement ")(id)
(" ended with incorrect identifier: ")(opt-id)),
let $t_2 = \text{enter}(t_1)(q)(\text{id})(<\varepsilon,\mathbf{*PROCESSNAME*},\text{p,ff,ref}^*>)$ **in**
let $p_1 = \%(p)(\text{id})$ **in**
let $t_3 = \text{enter}(\text{extend}(t_2)(p)(\text{id}))(p_1)(\mathbf{*UNIT*})(<\varepsilon,\mathbf{*PROCESS*}>)$ **in**
let $t_4 = \text{enter}(t_3)(p_1)(\mathbf{*LAB*})(<\varepsilon,\varepsilon>)$ **in**
let $t_5 = \text{enter}(t_4)(p_1)(\mathbf{*USED*})(<\varepsilon,\varepsilon>)$ **in**
let $t_6 = \text{enter}(t_5)(p_1)(\mathbf{*IMPT*})(<\varepsilon,\varepsilon,\varepsilon>)$ **in**
let $t_7 = \text{enter}(t_6)(p_1)(\mathbf{*SENS*})(<\varepsilon,\varepsilon>)$ **in**
$\underline{\mathbf{SLT}}\ [\![\ \text{ref}^*\ ]\!]\ (p_1)(u_2)(t_7)$
where $u_2 = \lambda t.\underline{\mathbf{DT}}\ [\![\ \text{decl}^*\ ]\!]\ (p_1)(tt)(u_1)(t)$
where $u_1 = \lambda t.\underline{\mathbf{SST}}\ [\![\ \text{seq-stat}^*\ ]\!]\ (p_1)(u)(t)))$

find-architecture-env(t)(p)
= (null(p)∨ tag(t(p)(*UNIT*))= ***ARCHITECTURE*** → p,
find-architecture-env(t)(rest(p)))

```
(CST3) CST [[ SEL-SIGASSN atmark delay-type id expr ref selected-waveform+ ]] (p)(u)(t)
       = let expr* = cons(expr,
                         collect-expressions-from-selected-waveforms
                           (selected-waveform+)) in
           let ref* = delete-duplicates
                        (collect-signals-from-expr-list(expr*)(t)(p)(ε)) in
            let case-alt+ = construct-case-alternatives
                              (ref)(delay-type)(selected-waveform+) in
             let case-stat = (CASE ,atmark,expr,case-alt+) in
              let process-stat = (PROCESS ,id,ref*,ε,(case-stat),id) in
               CST [[ process-stat ]] (p)(u)(t)

collect-expressions-from-selected-waveforms(selected-waveform*)
= (null(selected-waveform*)→ ε,
   let selected-waveform = hd(selected-waveform*) in
    let waveform = second(selected-waveform)
        and discrete-range+ = third(selected-waveform) in
     let transaction-exprs = collect-transaction-expressions(second(waveform)) in
      nconc
         (transaction-exprs,
         cons(second(discrete-range+),
         cons(third(discrete-range+),
         collect-expressions-from-selected-waveforms
            (tl(selected-waveform*))))))

collect-transaction-expressions(trans*)
= (null(trans*)→ ε,
   let transaction = hd(trans*) in
    cons(second(transaction),collect-transaction-expressions(tl(trans*))))

collect-signals-from-expr-list(expr*)(t)(p)(signal-refs)
= (null(expr*)→ signal-refs,
   let expr = hd(expr*) in
    collect-signals-from-expr
      (expr)(t)(p)(collect-signals-from-expr-list(tl(expr*))(t)(p)(signal-refs)))

collect-signals-from-expr(expr)(t)(p)(signal-refs)
= (¬consp(expr)→ signal-refs,
   is-ref?(expr)
   → let d = lookup-desc-for-ref(expr)(p)(t) in
       (tag(d)= *OBJECT* ∧ is-sig?(type(d))
        → cons(expr,
           (consp(second(expr))
            → collect-signals-from-expr-list(second(expr))(t)(p)(signal-refs),
            collect-signals-from-expr(second(expr))(t)(p)(signal-refs))),
         (consp(second(expr))
          → collect-signals-from-expr-list(second(expr))(t)(p)(signal-refs),
          collect-signals-from-expr(second(expr))(t)(p)(signal-refs))),
   is-paggr?(expr)
   → collect-signals-from-expr-list(second(expr))(t)(p)(signal-refs),
   is-unary-op?(hd(expr))
   → collect-signals-from-expr(second(expr))(t)(p)(signal-refs),
   is-binary-op?(hd(expr))∨ is-relational-op?(hd(expr))
   → collect-signals-from-expr
        (second(expr))(t)(p)
        (collect-signals-from-expr(third(expr))(t)(p)(signal-refs)),
   collect-signals-from-expr-list(expr)(t)(p)(signal-refs))
```

```
lookup-desc-for-ref(ref)(p)(t)
= let name = second(ref) in
    let id+ = (consp(last(name))→ rest(name), name) in
     let q = access(rest(id+))(t)(p) in
      lookup-desc-on-path(t)(q)(last(id+))

lookup-desc-on-path(t)(p)(id)
= let d = t(p)(id) in
    (d = *UNBOUND* → lookup-desc-on-path(t)(rest(p))(id), d)

access(id*)(t)(p)
= (null(id*)→ p,
   let id = hd(id*) in
    let d = lookup(t)(p)(id) in
     (d = *UNBOUND* → error(cat("Unbound identifier: ")(id)),
      access(tl(id*))(t)(%(path(d))(idf(d)))))

construct-case-alternatives(ref)(delay-type)(selected-waveform*)
= (null(selected-waveform*)→ ε,
   let selected-waveform = hd(selected-waveform*) in
    let waveform = second(selected-waveform)
        and discrete-range+ = third(selected-waveform) in
     let sig-assn-stat = (SIGASSN ,(AT ,mk-atmark()),delay-type,ref,waveform) in
      let case-alt = (CASECHOICE ,discrete-range+,(sig-assn-stat)) in
       cons(case-alt,
       construct-case-alternatives(ref)(delay-type)(tl(selected-waveform*))))


(CST4) CST ⟦ COND-SIGASSN atmark delay-type id ref cond-waveform* waveform ⟧ (p)(u)(t)
       = let expr* = nconc
                       (collect-expressions-from-conditional-waveforms
                          (cond-waveform*),
                       collect-transaction-expressions(second(waveform))) in
           let ref* = delete-duplicates
                       (collect-signals-from-expr-list(expr*)(t)(p)(ε)) in
            (null(cond-waveform*)
             → let sig-assn-stat = (SIGASSN ,(AT ,mk-atmark()),delay-type,ref,waveform) in
                 let process-stat = (PROCESS ,id,ref*,ε,(sig-assn-stat),id) in
                  CST ⟦ process-stat ⟧ (p)(u)(t),
              let cond-part+ = construct-cond-parts
                                 (ref)(delay-type)(cond-waveform*)
                  and else-part = ((SIGASSN ,(AT ,mk-atmark()),delay-type,ref,waveform)) in
               let if-stat = (IF ,atmark,cond-part+,else-part) in
                let process-stat = (PROCESS ,id,ref*,ε,(if-stat),id) in
                 CST ⟦ process-stat ⟧ (p)(u)(t))

collect-expressions-from-conditional-waveforms(cond-waveform*)
= (null(cond-waveform*)→ ε,
   let cond-waveform = hd(cond-waveform*) in
    let waveform = second(cond-waveform)
        and condition = third(cond-waveform) in
     let transaction-exprs = collect-transaction-expressions(second(waveform)) in
      nconc
         (transaction-exprs,
         cons(condition,
         collect-expressions-from-conditional-waveforms(tl(cond-waveform*)))))
```

```
construct-cond-parts(ref)(delay-type)(cond-waveform*)
= (null(cond-waveform*)→ ε,
   let cond-waveform = hd(cond-waveform*) in
    let waveform = second(cond-waveform)
        and condition = third(cond-waveform) in
     let sig-assn-stat = (SIGASSN ,(AT ,mk-atmark()),delay-type,ref,waveform) in
      let cond-part = (condition,(sig-assn-stat)) in
       cons(cond-part,construct-cond-parts(ref)(delay-type)(tl(cond-waveform*))))
```

6.5.7 Sensitivity Lists

(SLT0) $\underline{\mathbf{SLT}}$ ⟦ ε ⟧ (p)(u)(t) = u(t)

(SLT1) $\underline{\mathbf{SLT}}$ ⟦ ref ref* ⟧ (p)(u)(t)
= $\underline{\mathbf{SLT}}$ ⟦ ref ⟧ (p)(u_1)(t)
where u_1 = λt.$\underline{\mathbf{SLT}}$ ⟦ ref* ⟧ (p)(u)(t)

The **ref**s in the sensitivity list of a PROCESS statement are checked in sequential order.

```
(SLT2) SLT ⟦ REF name ⟧ (p)(u)(t)
       = let expr = ref in
           ET ⟦ expr ⟧ (p)(k)(t)
           where
           k = λ(w,e),t.
                 let d = tdesc(w) in
                  (¬is-sig?(w)
                   → error
                        (cat("Non-signal in process sensitivity list: ")(ref)),
                   let d1 = lookup(t)(p)(*SENS* ) in
                    let t1 = enter
                                (t)(p)(*SENS* )
                                (<ε,(cons(SLX ⟦ ref ⟧ (p)(t),sensitivity(d1)))>) in
                      u(t1))
```

6.5.8 Sequential Statements

(SST0) $\underline{\mathbf{SST}}$ ⟦ ε ⟧ (p)(c)(t) = c(t)

(SST1) $\underline{\mathbf{SST}}$ ⟦ seq-stat seq-stat* ⟧ (p)(c)(t)
= $\underline{\mathbf{SST}}$ ⟦ seq-stat ⟧ (p)(c_1)(t)
where c_1 = λt.$\underline{\mathbf{SST}}$ ⟦ seq-stat* ⟧ (p)(c)(t)

Sequential statements are statically checked in the textual order of their appearance in the hardware description.

(SST2) $\underline{\mathbf{SST}}$ ⟦ **NULL** atmark ⟧ (p)(c)(t) = c(t)

NULL statements require no checking.

```
(SST3) SST [[ VARASSN atmark ref expr ]] (p)(c)(t)
       = let expr0 = ref in
           ET [[ expr0 ]] (p)(k)(t)
           where
           k = λ(w,e),t.
                 let d = tdesc(w) in
                  (¬is-var?(w)
                   → error
                        (cat("Illegal target in variable assignment statement: ")
                         (seq-stat)),
                   ¬is-writable?(w)
                   → error(cat("Read-only variable: ")(namef(d))),
                   RT [[ expr ]] (p)(k1)(t)
                    where
                    k1 = λ(w1,e1),t.
                           let d1 = tdesc(w1) in
                            (match-types(d,d1)→ c(t),
                             error(cat("Assignment type mismatch: ")(d)(d1))))

find-process-env(t)(p)
= (null(p)∨ tag(t(p)(*UNIT* ))= *PROCESS* → p, find-process-env(t)(rest(p)))
```

First the left part of a variable assignment statement is checked, and then the right part. The left part must be a variable of reference type (checked by **is-var?** and **is-writable?**), and the basic types of the left and right parts must be the same, as verified by **match-types** (refer to the definitions following semantic function **DT5**).

```
(SST4) SST [[ SIGASSN atmark delay-type ref waveform ]] (p)(c)(t)
       = let expr = ref in
           ET [[ expr ]] (p)(k)(t)
           where
           k = λ(w,e),t.
                 let d = tdesc(w)
                     and q = find-process-env(t)(p) in
                  (¬is-sig?(w)
                   → error
                        (cat("Illegal target of signal assignment statement: ")
                         (namef(d))),
                   ¬is-writable?(w)→ error
                                       (cat("Read-only signal: ")(namef
                                                                  (d))),
                    null(q)
                    → error
                         (cat("Sequential signal assignment statement not in a process: ")
                          (seq-stat)),
                    let d1 = lookup-desc-for-ref(ref)(p)(t) in
                     (null(process(d1))
                      → let t1 = enter
                                   (t)(path(d1))(idf(d1))
                                   (<ε,*OBJECT* ,path(d1),exported(d1),type(d1),
                                     value(d1),last(q)>) in
                          c1(t1),
                      process(d1)= last(q)→ c1(t),
                      error
                        (cat("Target of signal assignments in multiple processes: ")
```

```
        (namef(d1))))
    where
    c1 = λt1.WT [[ waveform ]] (p)(k1)(t)
          where
          k1 = λ(w1,e1),t.
                let d1 = tdesc(w1) in
                 (match-types(d,d1)→ c(t),
                  error
                    (cat("Assignment type mismatch: ")
                     (d)(d1))))
```

```
(SST5) SST [[ IF atmark cond-part+ else-part ]] (p)(c)(t)
       = let seq-stat* = else-part in
           check-if(cond-part+)(p)(c1)(t)
            where c1 = λt.(null(seq-stat*)→ c(t), SST [[ seq-stat* ]] (p)(c)(t))

check-if(cond-part*)(p)(c)(t)
= (null(cond-part*)→ c(t),
   let (expr,seq-stat*) = hd(cond-part*) in
    RT [[ expr ]] (p)(k)(t)
     where
     k = λ(w,e),t.
          (is-boolean?(w)
           → SST [[ seq-stat* ]] (p)(c1)(t)
                where c1 = λt.check-if(tl(cond-part*))(p)(c)(t),
           error(cat("Non-boolean condition in IF statement: ")(tdesc
                                                                (w)))))
```

A Stage 3 VHDL IF statement consists of one or more conditional parts (**cond-parts**) followed by a (possibly empty) **else-part**. Each **cond-part** consists of a test expression followed by sequential statements that are to be executed when the test expression is the first to evaluate to **true**; the sequential statements constituting the **else-part** are to be executed when none of the test expressions is **true**.

The **cond-parts** are first checked, in order, by auxiliary semantic function **check-if**, after which the **else-part**, if nonempty, is checked by **SST**. Checking each **cond-part** involves first ascertaining that the basic type of its test expression is boolean, and then invoking **SST** to check its sequential statements.

```
(SST6) SST [[ CASE atmark expr case-alt+ ]] (p)(c)(t)
       = RT [[ expr ]] (p)(k)(t)
          where
          k = λ(w,e),t1.
                let d = get-base-type(tdesc(w)) in
                 AT [[ case-alt+ ]] (d)(p)(y)(t1)
                  where
                  y = λh,t2.
                       (¬case-type-ok(d)
                        → error
                             (cat("Illegal CASE selector type: ")(namef(d))
                              (seq-stat)),
                        ¬case-coverage(d)(h)
                        → error
                             (cat("Incomplete CASE coverage for type: ")
                              (namef(d))(seq-stat)),
                        c(t2))
```

```
case-type-ok(d)
= is-boolean-tdesc?(d)∨ is-bit-tdesc?(d)

case-coverage(d)(h)
= (is-boolean-tdesc?(d)∧ set-card(h)= 2)
   ∨ (is-bit-tdesc?(d)∧ set-card(h)= 2)

set-card(x) = length(x)
```

A Stage 3 VHDL CASE statement consists of a selector expression followed by one or more *case alternatives*, each consisting of sequential statements preceded either by a nonempty sequence of discrete ranges or by the reserved word OTHERS. This discrete range sequence defines a *case selection set* for the particular case alternative.

The Stage 3 VHDL concrete syntax allows the statements in a case alternative to be preceded by a list of discrete ranges and *expressions*; for uniformity, in the Phase 1 abstract syntax (generated by the Stage 3 VHDL parser) these expressions are converted into equivalent one-element discrete ranges.

A CASE statement must be checked for the following:

- The basic type of *all* the case selection sets (and thus of the expressions that define the discrete ranges) must be the same, and must match that of the selector expression. In Stage 3 VHDL, the only such basic types are **BOOLEAN**, **BIT**, **INTEGER**, and enumeration types (including **CHARACTER**).
- Every expression of every discrete range in a CASE statement must be *static*, i.e., must have a value defined by Phase 1. This enables the contents of each case selection set to be determined during Phase 1. The OTHERS alternative, if present, defines a case selection set that is the *complement* of the union of the other case selection sets with respect to the set of values associated with the basic type. The **BOOLEAN** basic type is associated with the set of truth values {**FALSE**, **TRUE**}, the **BIT** basic type with the set of bit values {0, 1}, the **INTEGER** basic type with the set of integers {..., -2, -1, 0, 1, 2, ...}, the **CHARACTER** basic type with the set {(**CHAR 0**), ..., (**CHAR 127**)} of ASCII-128 character representations, and an arbitrary enumeration type with the set of its enumeration literals.
- The selection sets for each case alternative must be *mutually disjoint*, and their union must be the set associated with the basic type of the selector expression. The case selection subsets defined by the discrete ranges within each case alternative need not be disjoint. Note that a CASE statement with a selection expression of basic type **INTEGER** *must* have an OTHERS alternative, as the set of integers cannot be covered by a finite number of case alternatives, each with only a finite number of (finite) discrete ranges.

The basic type of the selector expression is first determined. Then semantic function **AT** is invoked with this basic type to check the case alternatives. Refer to the discussion of **AT**, which returns the union of the case selection sets associated with all of the case alternatives, a union that must cover the set associated with the selector expression's basic type.

```
(SST7) SST [[ LOOP atmark id seq-stat* opt-id ]] (p)(c)(t)
       = let q = find-looplabel-env(t)(p) in
           let labels = third(t(q)(*LAB* )) in
            (id ∈ labels → error(cat("Duplicate loop label: ")($(q)(id))),
             let t1 = enter(t)(q)(*LAB* )((ε,cons(id,labels))) in
              (¬null(opt-id)∧ opt-id ≠ id
               → error
                     (cat("Loop ")(id)(" ended with incorrect identifier: ")(opt-id)),
               let t2 = enter(t1)(q)(id)(<ε,*LOOPNAME* ,p>) in
                let p1 = %(p)(id) in
                 let t3 = enter(extend(t2)(p)(id))(p1)(*UNIT* )(<ε,*LOOP* >) in
                  let t4 = enter(t3)(p1)(*LAB* )(<ε,ε>) in
                   let t5 = enter(t4)(p)(id)(<ε,*LOOPNAME* ,p>) in
                    let c1 = λt.SST [[ seq-stat* ]] (p1)(c)(t) in
                     c1(t5)))

(SST8) SST [[ WHILE atmark id expr seq-stat* opt-id ]] (p)(c)(t)
       = let q = find-looplabel-env(t)(p) in
           let labels = third(t(q)(*LAB* )) in
            (id ∈ labels → error(cat("Duplicate loop label: ")($(q)(id))),
             let t1 = enter(t)(q)(*LAB* )((ε,cons(id,labels))) in
              (opt-id ≠ ε ∧ opt-id ≠ id
               → error
                     (cat("Loop ")(id)(" ended with incorrect identifier: ")(opt-id)),
               let t2 = enter(t1)(q)(id)(<ε,*LOOPNAME* ,p>) in
                let p1 = %(p)(id) in
                 let t3 = enter(extend(t2)(p)(id))(p1)(*UNIT* )(<ε,*LOOP* >) in
                  let t4 = enter(t3)(p1)(*LAB* )(<ε,ε>) in
                   let t5 = enter(t4)(p)(id)(<ε,*LOOPNAME* ,p>) in
                    let c1 = λt.SST [[ seq-stat* ]] (p1)(c)(t) in
                     RT [[ expr ]] (p1)(k)(t5)
                      where
                      k = λ(w,e),t.
                            (is-boolean?(w)→ c1(t),
                             error
                                (cat("Non-boolean condition in WHILE statement: ")
                                 (tdesc(w))))))

(SST9) SST [[ FOR atmark id ref discrete-range seq-stat* opt-id ]] (p)(c)(t)
       = let q = find-looplabel-env(t)(p) in
           let labels = third(t(q)(*LAB* )) in
            (id ∈ labels → error(cat("Duplicate loop label: ")($(q)(id))),
             let t1 = enter(t)(q)(*LAB* )((ε,cons(id,labels))) in
              (¬null(opt-id)∧ opt-id ≠ id
               → error
                     (cat("Loop ")(id)(" ended with incorrect identifier: ")(opt-id)),
               let t2 = enter(t1)(q)(id)(<ε,*LOOPNAME* ,p>) in
                let p1 = %(p)(id) in
                 let t3 = enter(extend(t2)(p)(id))(p1)(*UNIT* )(<ε,*LOOP* >) in
                  let t4 = enter(t3)(p1)(*LAB* )(<ε,ε>) in
                   let t5 = enter(t4)(p)(id)(<ε,*LOOPNAME* ,p>) in
                    let (direction,expr1,expr2) = discrete-range in
                     RT [[ expr1 ]] (p)(k1)(t)
                      where
                      k1 = λ(w1,e1),t.
                            let d1 = tdesc(w1) in
                             RT [[ expr2 ]] (p)(k2)(t)
```

```
                    where
                    k2 = λ(w2,e2),t.
                          let d2 = tdesc(w2) in
                           (match-types(d1,d2)
                            → let decl = (DEC ,CONST ,
                                          (hd(hd(tl(ref)))),
                                          (hd(d1)),
                                          hd(tl(discrete-range))) in
                                DT [[ decl ]] (p1)(tt)(u)(t5),
                              error
                                 (cat("Bounds type mismatch in FOR statement: ")
                                  (seq-stat)))
          where
          u = λt6.c1(t6)
                where c1 = λt7.SST [[ seq-stat* ]] (p1)(c)(t7)))

find-looplabel-env(t)(p)
= let tg = tag(t(p)(*UNIT* )) in
    (null(p)∨ tg ∈ (*PROCESS* *PROCEDURE* *FUNCTION* *LOOP*) → p,
     find-looplabel-env(t)(rest(p)))
```

In Stage 3 VHDL, entering a loop (i.e., a `LOOP`, `WHILE` or `FOR` statement) creates a new component environment of the TSE, just as in the case of entering a subprogram (see below). The identifier that is the loop's label must be checked for uniqueness among the identifiers used thus far as labels in the innermost enclosing program unit (process, procedure, function, or loop). If unique, the identifier is appended to the innermost enclosing unit's label identifier list (bound to the special identifier ***LAB*** of the corresponding environment).

A ***LOOPNAME*** descriptor is then entered into the current environment. The resulting TSE is extended to reflect loop entry; the ***UNIT*** entry in the extended TSE is set to ***LOOP*** to associate the extended TSE with the loop, and the ***LOOPNAME*** descriptor is also entered into the extended TSE. This latter descriptor is used by `EXIT` statements contained in this loop to validate the visibility of their loop names.

In the case of a `WHILE` loop, the basic type of the iteration control expression is checked to be **BOOLEAN**, and the loop body is also checked by **SST**.

In the case of a `FOR` loop, the basic types of the iteration bounds expressions are checked to match, the implicit declaration of the iteration parameter is processed by semantic function **DT**, and the loop body is checked with **SST**.

```
(SST10) SST [[ EXIT atmark opt-dotted-name opt-expr ]] (p)(c)(t)
        = (null(find-loop-env(t)(p))
           → error(cat("EXIT statement not in a loop: ")(seq-stat)),
           (null(opt-dotted-name)→ c1(t),
            name-type(opt-dotted-name)(ε)(p)(t)(v)
             where
             v = λw.(tag(tdesc(w))≠ *LOOPNAME*
                   → error(cat("Not a loop name: ")(namef(tdesc(w)))),
                   c1(t)))
             where
             c1 = λt.(null(opt-expr)→ c(t),
                   let expr = opt-expr in
```

```
RT [[ expr ]] (p)(k)(t)
where
k = λ(w,e),t.
      (is-boolean?(w)→ c(t),
       error
          (cat("Non-boolean condition in EXIT statement: ")
           (tdesc(w))))))
```

An EXIT statement must be contained within a loop; otherwise, an error is raised. If an exit control expression is present, its basic type is checked; if not **BOOLEAN**, an error is raised.

```
(SST11) SST [[ CALL atmark ref ]] (p)(c)(t)
        = let expr = ref in
            ET [[ expr ]] (p)(k)(t)
            where
            k = λ(w,e),t.
                  (tag(tdesc(w))= *VOID* → c(t),
                   error(cat("Invalid procedure call: ")(seq-stat)))
```

A procedure call statement boils down to an expression that is a Stage 3 VHDL name. This expression is checked by **ET**, and must have a **VOID** basic type.

```
(SST12) SST [[ RETURN atmark opt-expr ]] (p)(c)(t)
        = let d = context(t)(p) in
            let tg = tag(d)
                and cname = namef(d) in
             (null(opt-expr)
              → (tg ≠ *PROCEDURE*
                   → error
                        (cat("RETURN without expression in context of non-procedure: ")
                         (cname)(seq-stat)),
                 c(t)),
              (tg ≠ *FUNCTION*
               → error
                    (cat("RETURN with expression in context of non-function: ")
                     (cname)(seq-stat)),
               let expr = opt-expr in
                RT [[ expr ]] (p)(k)(t)
                where
                k = λ(w,e),t.
                      (map-match-types(tdesc(w))(extract-rtypes(signatures(d)))
                       → c(t),
                       error
                          (cat("Incorrect return expression type in function: ")
                           (cname)(seq-stat)))))


context(t)(path)
= let d = t(path)(*UNIT* ) in
    (d = *UNBOUND* → context(t)(rest(path)),
     (case tag(d)
        (*PROCEDURE* ,*FUNCTION* ,*PACKAGE* ) → t(rest(path))(last(path)),
        OTHERWISE → context(t)(rest(path))))
```

```
extract-rtypes(signatures)
= (null(signatures)→ ε,
   cons(tdesc(rtype(hd(signatures))),extract-rtypes(tl(signatures))))
```

RETURN statements have two forms, depending on the PROCEDURE or FUNCTION context in which they can appear. Auxiliary semantic function **context** returns the descriptor of the smallest subprogram or package enclosing the program text whose local environment is at the end of the current path. It is first determined whether the RETURN statement is in the proper context. If so, then if the RETURN statement has an expression, its basic type must be equal to the basic type of the result type of the function in which it appears.

```
(SST13) SST [[ WAIT atmark ref* opt-expr1 opt-expr2 ]] (p)(c)(t)
        = let c1 = λt.let d = lookup(t)(p)(*SENS* ) in
                      (¬null(sensitivity(d))
                       → error
                            (cat("WAIT statement ")(seq-stat)
                             (" illegal in process with sensitivity list: ")
                             (last(p))),
                       let c2 = λt.(null(opt-expr2)→ c(t),
                                    let expr2 = opt-expr2 in
                                     RT [[ expr2 ]] (p)(k2)(t)
                                      where
                                      k2 = λ(w2,e2),t2.
                                             (is-time?(w2)→ c(t2),
                                              error
                                                 (cat("Ill-typed timeout clause in WAIT statement: ")
                                                  (seq-stat)))) in
                        (null(opt-expr1)→ c2(t),
                         let expr1 = opt-expr1 in
                          RT [[ expr1 ]] (p)(k1)(t)
                           where
                           k1 = λ(w1,e1),t1.
                                  (is-boolean?(w1)→ c2(t1),
                                   error
                                      (cat("Non-boolean condition clause in WAIT statement: ")
                                       (seq-stat))))) in
             check-wait-refs(seq-stat)(ref*)(p)(c1)(t)

check-wait-refs(seq-stat)(ref*)(p)(c)(t)
= (null( [[ ref* ]] )→ c(t),
   let ref = hd(ref*)
       and c1 = λt.check-wait-refs(seq-stat)(tl(ref*))(p)(c)(t) in
    check-wait-ref(seq-stat)(ref)(p)(c1)(t))

check-wait-ref(seq-stat)(ref)(p)(c)(t)
= let expr = ref in
   ET [[ expr ]] (p)(k)(t)
   where
   k = λ(w,e),t.
        let d = tdesc(w) in
         (d = *UNBOUND* → error(cat("Unbound identifier: ")(namef
                                                              (d))),
          (is-sig?(w)→ c(t),
           error
              (cat("Non-signal ")(ref)
               (" in sensitivity clause of WAIT statement: ")
               (seq-stat))))
```

Semantic equation **SST13** specifies the static semantics of the `WAIT` statement. which consists of a sensitivity list **ref***, an optional condition **opt-expr**$_1$, and an optional timeout expression **opt-expr**$_2$. First, auxiliary semantic function **check-wait-refs** recursively traverses the sensitivity list, checking that each **ref** denotes a declared signal. Next, a descriptor for the special identifier ***SENS*** is looked up, and if its *sensitivity* field is nonempty, then the `WAIT` statement illegally appears inside a `PROCESS` statement with a sensitivity list. If present, the condition is checked to have basic type **BOOLEAN**. Finally, if present, the timeout expression is checked to have basic type **TIME**.

6.5.9 Case Alternatives

(AT0) $\underline{\mathbf{AT}}$ ⟦ ε ⟧ (d)(p)(y)(t) = y(emptyset)(t)

(AT1) $\underline{\mathbf{AT}}$ ⟦ case-alt* case-alt ⟧ (d)(p)(y)(t)
= $\underline{\mathbf{AT}}$ ⟦ case-alt* ⟧ (d)(p)(y_1)(t)
where
$y_1 = \lambda h_1,t_1.$
$\underline{\mathbf{AT}}$ ⟦ case-alt ⟧ (d)(p)(y_2)(t_1)
where
$y_2 = \lambda h_2,t_2.$
(case-overlap(d)((h_1,h_2))
→ error
(cat("`Overlapping case alternatives for type: `")
(namef(d))),
y(case-union(d)((h_1,h_2)))(t_2))

(AT2) $\underline{\mathbf{AT}}$ ⟦ **CASECHOICE** discrete-range$^+$ seq-stat* ⟧ (d)(p)(y)(t)
= $\underline{\mathbf{DRT}}$ ⟦ discrete-range$^+$ ⟧ (d)(p)(y_1)(t)
where
$y_1 = \lambda h,t_1.$
$\underline{\mathbf{SST}}$ ⟦ seq-stat* ⟧ (p)(c)(t_1)
where $c = \lambda t_2.y(h)(t_2)$

(AT3) $\underline{\mathbf{AT}}$ ⟦ **CASEOTHERS** seq-stat* ⟧ (d)(p)(y)(t)
= $\underline{\mathbf{SST}}$ ⟦ seq-stat* ⟧ (p)(c)(t)
where
$c = \lambda t_1.$y((is-boolean-tdesc?(d)→ {**FALSE** ,**TRUE** },
is-bit-tdesc?(d)→ {0,1},
is-integer-tdesc?(d)→ **INT** ,
is-enumeration-tdesc?(d)→ **ENUM** ,
error
(cat("`Illegal CASE selector type: `")(namef(d))(case-alt))))
(t_1)

case-overlap(d)(x,y)
= ((is-integer-tdesc?(d)∧ (x = **INT** ∨ y = **INT**))
∨ (is-enumeration-tdesc?(d)∧ (x = **ENUM** ∨ y = **ENUM**))
→ ff,
x ∩ y ≠ emptyset)

case-union(d)(x,y)
= (is-integer-tdesc?(d)∧ (x = **INT** ∨ y = **INT**) → **INT** ,
is-enumeration-tdesc?(d)∧ (x = **ENUM** ∨ y = **ENUM**) → **ENUM** ,
x ∪ y)

Semantic function **AT** processes each case alternative in turn, beginning with the last one. As the case selection set of each alternative is computed, it is checked for disjointness with the union of the selection sets of the preceding alternatives. If disjoint, then the union of these two case selection sets is returned; otherwise an error is raised.

Note that the case selection set of an `OTHERS` alternative (represented by `CASEOTHERS` in the abstract syntax) is *always* disjoint from the union of the selection sets of the preceding alternatives, because (1) a `CASE` statement can contain at most one such alternative; (2) if such an alternative is present, it must be the last alternative; and (3) the case selection set of an `OTHERS` alternative is the relative complement of the union of the case selection sets of the preceding alternatives.

AT invokes the semantic function **DRT** to compute the case selection set defined by the sequence of discrete ranges of a particular case alternative.

6.5.10 Discrete Ranges

(DRT0) **DRT** ⟦ ε ⟧ (d)(p)(y)(t) = y(emptyset)(t)

(DRT1) **DRT** ⟦ discrete-range discrete-range* ⟧ (d)(p)(y)(t)
= **DRT** ⟦ discrete-range ⟧ (d)(p)(y_1)(t)
where
$y_1 = \lambda h_1,t_1.$
DRT ⟦ discrete-range* ⟧ (d)(p)(y_2)(t_1)
where $y_2 = \lambda h_2,t_2.y(h_1 \cup h_2)(t_2)$

A sequence of discrete ranges is processed in order, from left to right.

(DRT2) **DRT** ⟦ discrete-range ⟧ (d)(p)(y)(t)
= **let** (direction,$expr_1$,$expr_2$) = discrete-range **in**
RT ⟦ $expr_1$ ⟧ (p)(k_1)(t)
where
$k_1 = \lambda(w_1,e_1),t_1.$
(¬match-types(d,tdesc(w_1))
→ error(cat("**CASE type mismatch:** ")(d)(tdesc(w_1))),
e_1 = ***UNDEF***
→ error(cat("**Non-static CASE expression:** ") ⟦ $expr_1$ ⟧),
RT ⟦ $expr_2$ ⟧ (p)(k_2)(t_1)
where
$k_2 = \lambda(w_2,e_2),t_2.$
(¬match-types(d,tdesc(w_2))
→ error
(cat("**CASE type mismatch:** ")(d)(tdesc
(w_2))),
e_2 = ***UNDEF***
→ error
(cat("**Non-static CASE expression:** ")
⟦ $expr_2$ ⟧),
y(mk-set(d)((direction,e_1,e_2)))(t_2)))

mk-set(d)(direction,e_1,e_2)
= (case tag(d)
BOOL

```
    → (e1 = e2 → {e1},
        (direction = TO → (e1 = FALSE ∧ e2 = TRUE → {FALSE ,TRUE }, emptyset),
         (e1 = TRUE ∧ e2 = FALSE → {TRUE ,FALSE }, emptyset))),
    *BIT*
    → (e1 = e2 → {e1},
        (direction = TO → (e1 = 0 ∧ e2 = 1 → {0,1}, emptyset), (e1 = 1 ∧ e2 = 0 → {1,0}, emptyset))),
    (*INT* ,*INT_TYPE* )
    → (direction = TO
        → (e1 ≤ e2 → {e1} ∪ mk-set(d)((direction,(e1+1),e2)), emptyset),
        (e1 ≥ e2 → {e1} ∪ mk-set(d)((direction,(e1−1),e2)), emptyset)),
    *ENUMTYPE*
    → (direction = TO → mk-enum-set(literals(d))(e1)(e2),
        mk-enum-set(reverse(literals(d)))(e1)(e2)),
    OTHERWISE → error(cat("Illegal CASE expression type tag: ")(tag(d))))

mk-enum-set(id+)(id1)(id2)
= let n1 = position(id1)(id+)
      and n2 = position(id2)(id+) in
    (n2 < n1 → ε,
     nth-tl(n1)(reverse(nth-tl(length(id+)−(n2+1))(reverse(id+)))))

nth-tl(n)(x) = (n = 0 → x, nth-tl(n−1)(tl(x)))

position(a)(x) = position-aux(a)(x)(0)

position-aux(a)(x)(n)
= (null(x)→ ff, (a = hd(x)→ n, position-aux(a)(tl(x))(1+n)))

reverse(x) = reverse-aux(x)(ε)

reverse-aux(x)(y) = (null(x)→ y, reverse-aux(tl(x))(cons(hd(x),y)))
```

Semantic function **DRT** receives a case selector expression's basic type from **AT**. **DRT** detects a mismatch between the basic type of a discrete range and that of the selector expression; it also detects the presence of nonstatic expressions in a discrete range. Case selection sets are constructed by the function **mk-set** ("make set"), which takes a type descriptor and a pair of translated *static* expressions that represent a discrete range (that the expressions are static is checked in Phase 1) and returns the corresponding set of values.

6.5.11 Waveforms and Transactions

```
(WT1) WT ⟦ WAVE transaction+ ⟧ (p)(k)(t) = TRT ⟦ transaction+ ⟧ (p)(k)(t)

(TRT1) TRT ⟦ transaction transaction* ⟧ (p)(k)(t)
       = TRT ⟦ transaction ⟧ (p)(k1)(t)
          where
          k1 = λ(w1,e1),t1.
                 let d1 = tdesc(w1) in
                  (null(transaction*)→ k((w1,e1))(t1),
                   let transaction1+ = transaction* in
                    TRT ⟦ transaction1+ ⟧ (p)(k2)(t1)
                     where
                     k2 = λ(w2,e2),t2.
                            let d2 = tdesc(w2) in
```

```
                    (¬match-types(d1,d2)
                     → error
                          (cat("Type mismatch for waveform transactions: ")
                           (transaction)(hd(transaction1+ ))),
                     e1 ≠ *UNDEF* ∧ e2 ≠ *UNDEF*
                     → (e1 ≥ e2
                        → error
                             (cat("Nonascending times for waveform transactions: ")
                              (transaction)(hd(transaction1+ ))),
                        k((w2,e2))(t2)),
                     k((w2,e1))(t2)))
```

(TRT2) **TRT** ⟦ **TRANS** expr opt-expr ⟧ (p)(k)(t)
= **RT** ⟦ expr ⟧ (p)(k_1)(t)
where
$k_1 = \lambda(w_1,e_1),t_1.$
(null(opt-expr)→ k((w_1,0))(t_1),
let $expr_2$ = opt-expr **in**
RT ⟦ $expr_2$ ⟧ (p)(k_2)(t_1)
where
$k_2 = \lambda(w_2,e_2),t_2.$
(¬is-time?(w_2)
→ error
(cat("Transaction has ill-typed time expression: ")
(tdesc(w_2))),
$e_2 \neq$ *UNDEF*
→ ($e_2 < 0$
→ error
(cat("Transaction has negative time expression: ")
(e_2)),
k((w_1,e_2))(t_2)),
k((w_1,e_2))(t_2)))

6.5.12 Expressions

(ET0) **ET** ⟦ ϵ ⟧ (p)(k)(t) = k((ϵ,ϵ))(t)

(ET1) **ET** ⟦ **FALSE** ⟧ (p)(k)(t) = k((mk-type((**CONST VAL**))(bool-type-desc(t)),**FALSE**))(t)

(ET2) **ET** ⟦ **TRUE** ⟧ (p)(k)(t) = k((mk-type((**CONST VAL**))(bool-type-desc(t)),**TRUE**))(t)

(ET3) **ET** ⟦ **BIT** bitlit ⟧ (p)(k)(t)
= k((mk-type((**CONST VAL**))(bit-type-desc(t)),**B** ⟦ bitlit ⟧))(t)

(ET4) **ET** ⟦ **NUM** constant ⟧ (p)(k)(t)
= k((mk-type((**CONST VAL**))(int-type-desc(t)),**N** ⟦ constant ⟧))(t)

(ET5) **ET** ⟦ **TIME** constant time-unit ⟧ (p)(k)(t)
= **let** normalized-constant = (case time-unit
FS → **N** ⟦ constant ⟧ ,
PS → 1000×**N** ⟦ constant ⟧ ,
NS → 1000000×**N** ⟦ constant ⟧ ,
US → 1000000000×**N** ⟦ constant ⟧ ,
MS → 1000000000000×**N** ⟦ constant ⟧ ,
SEC → 1000000000000000×**N** ⟦ constant ⟧ ,

```
                                MIN → 60×(1000000000000000×N ⟦ constant ⟧ ),
                                HR → 3600×(1000000000000000×N ⟦ constant ⟧ ),
                                OTHERWISE
                                → error
                                     (cat("Illegal unit name for physical type TIME: ")
                                      (time-unit))) in
          k((mk-type((CONST VAL) )(time-type-desc(t)),normalized-constant))(t)

(ET6) ET ⟦ CHAR constant ⟧ (p)(k)(t)
      = let expr = (CHAR ,constant) in
          let d = lookup(t)((STANDARD) )(expr) in
           k((type(d),idf(d)))(t)


(ET7) ET ⟦ BITSTR bit-lit* ⟧ (p)(k)(t)
      = let expr* = bit-lit* in
          (null(expr*)
           → k((mk-type((CONST VAL) )(lookup(t)(ε)(BIT_VECTOR )),*UNDEF* ))(t),
           list-type(expr*)(p)(t)(vv)
            where vv = λw*.array-type(BIT_VECTOR )(expr*)(w*)(t)(p)(k))

(ET8) ET ⟦ STR char-lit* ⟧ (p)(k)(t)
      = let expr* = char-lit* in
          (null(expr*)→ k((mk-type((CONST VAL) )(lookup(t)(ε)(STRING )),*UNDEF* ))(t),
           list-type(expr*)(p)(t)(vv)
            where vv = λw*.array-type(STRING )(expr*)(w*)(t)(p)(k))

array-type(array-type-name)(expr*)(w*)(t)(p)(k)
= let d = tdesc(hd(w*)) in
    (chk-array-type(d)(tl(w*))
     → let array-type-desc = array-type-desc
                              (new-array-type-name(array-type-name))(ε)(p)(tt)
                              (TO )((NUM 1) )((NUM ,length(w*)))(d) in
         k((mk-type(tmode(hd(w*)))(array-type-desc),*UNDEF* ))(t),
     error(cat("Array aggregate of inhomogeneous type: ")(expr*)))

chk-array-type(d)(w*)
= (null(w*)→ tt,
   match-types(d)(tdesc(hd(w*)))→ chk-array-type(d)(tl(w*)),
   ff)


(ET9) ET ⟦ REF name ⟧ (p)(k)(t)
      = name-type(name)(ε)(p)(t)(v)
          where
          v = λw.let d = tdesc(w) in
                 (second(tmode(w))= TYP
                  → error(cat("Wrong context for a type: ")(namef(d))(expr)),
                  tag(d)= *OBJECT* → k((type(d),value(d)))(t),
                  tag(d)= *ENUMELT* → k((type(d),idf(d)))(t),
                  k((w,*UNDEF* ))(t))


(ET10) ET ⟦ PAGGR expr* ⟧ (p)(k)(t)
       = (length(expr*)= 1
          → let expr = hd(expr*) in
              ET ⟦ expr ⟧ (p)(k)(t),
          list-type(expr*)(p)(t)(vv)
           where vv = λw*.array-type(*ANONYMOUS* )(expr*)(w*)(t)(p)(k))
```

```
(ET11) ET ⟦ unary-op expr ⟧ (p)(k)(t)
       = RT ⟦ expr ⟧ (p)(k1)(t)
         where k1 = λ(w,e),t.OT1 ⟦ unary-op ⟧ (k)((w,e))(t)

(ET12) ET ⟦ binary-op expr1 expr2 ⟧ (p)(k)(t)
       = RT ⟦ expr1 ⟧ (p)(k1)(t)
         where
         k1 = λ(w1,e1),t.
                RT ⟦ expr2 ⟧ (p)(k2)(t)
                 where k2 = λ(w2,e2),t.
                        OT2 ⟦ binary-op ⟧ (k)((w1,e1))((w2,e2))(t)

(ET13) ET ⟦ relational-op expr1 expr2 ⟧ (p)(k)(t)
       = RT ⟦ expr1 ⟧ (p)(k1)(t)
         where
         k1 = λ(w1,e1),t.
                RT ⟦ expr2 ⟧ (p)(k2)(t)
                 where
                 k2 = λ(w2,e2),t.
                        OT2 ⟦ relational-op ⟧ (k)((w1,e1))((w2,e2))(t)


(RT1) RT ⟦ expr ⟧ (p)(k)(t)
      = ET ⟦ expr ⟧ (p)(k1)(t)
        where
        k1 = λ(w,e),t.
               let tm = tmode(w)
                   and d = tdesc(w) in
                (second(tm)= ACC → error
                                       (cat("Non-value (an access): ")(expr)),
                 second(tm)= OUT
                 → error
                       (cat("Cannot dereference formal OUT parameter: ")(expr)),
                 second(tm)= VAL ∧ is-void-tdesc?(d)
                 → error(cat("Void value: ")(expr)),
                 let w1 = ((second(tm)= AGR → (DUMMY AGR) , (DUMMY VAL) ),tdesc(w)) in
                  k((w1,e))(t))


(OT1.1) OT1 ⟦ unary-op ⟧ (k)(w,e)(t)
        = let d = tdesc(w) in
          (match-types(d,argtypes1(unary-op)(d))
           → k((restype1(unary-op)(d),resval1(unary-op)(e)(d)))(t),
           error
             (cat("Argument type mismatch for unary operator: ")(unary-op)(d)))

argtypes1(unary-op)(d)
= (case unary-op
    NOT
    → (is-boolean-tdesc?(d)∨ is-bit-tdesc?(d)→ d,
       argtypes1-error(unary-op)(d)),
    (PLUS ,NEG ,ABS )
    → (is-integer-tdesc?(d)∨ is-time-tdesc?(d)→ d,
       argtypes1-error(unary-op)(d)),
    OTHERWISE → error
                      (cat("Unrecognized Stage 3 VHDL unary operator: ")(unary-op)))
```

```
argtypes1-error(unary-op)(d)
= error(cat("Unary operator ")(unary-op)(" not implemented for type: ")(d))

restype1(unary-op)(d) = mk-type((DUMMY VAL) )(d)

resval1(unary-op)(e)(d)
= (e = *UNDEF* → *UNDEF* ,
   (case unary-op
      NOT
      → (is-boolean-tdesc?(d)→ ¬e,
         is-bit-tdesc?(d)→ invert-bit(e),
         *UNDEF* ),
      PLUS → e,
      NEG → −e,
      ABS → abs(e),
      OTHERWISE → *UNDEF* ))

invert-bit(bitlit) = mk-bit-simp-symbol((−bitlit)+1)

mk-bit-simp-symbol(bitlit)
= (case bitlit
     0 → (BS 0 1) ,
     1 → (BS 1 1) ,
     OTHERWISE → error(cat("Can't construct simp symbol for bit: ")(bitlit)))


(OT2.1) OT2 [[ binary-op ]] (k)(w1,e1)(w2,e2)(t)
        = let d1 = tdesc(w1)
              and d2 = tdesc(w2) in
          (argtypes2(binary-op)((d1,d2))
           → k((restype2(binary-op)((d1,d2))(t),
                resval2((d1,d2))(binary-op)((e1,e2))))(t),
           error
             (cat("Argument type mismatch for binary operator: ")(binary-op)(d1)
              (d2)))

(OT2.2) OT2 [[ relational-op ]] (k)(w1,e1)(w2,e2)(t)
        = let d1 = tdesc(w1)
              and d2 = tdesc(w2) in
          (argtypes2(relational-op)((d1,d2))
           → k((mk-type((DUMMY VAL) )(bool-type-desc(t)),
                resval2((d1,d2))(relational-op)((e1,e2))))(t),
           error
             (cat("Argument type mismatch for relational operator: ")
              (relational-op)(d1)(d2)))

argtypes2(op)(d1,d2)
= (case op
     (AND ,NAND ,OR ,NOR ,XOR )
     → (case hd(d1)
          BOOLEAN → is-boolean-tdesc?(d2)∨ argtypes2-error(op)(d1)(d2),
          BIT → is-bit-tdesc?(d2)∨ argtypes2-error(op)(d1)(d2),
          OTHERWISE → argtypes2-error(op)(d1)(d2)),
     (ADD ,SUB )
     → (case hd(d1)
          (UNIVERSAL_INTEGER ,INTEGER )
          → match-types(d1)(d2)∨ argtypes2-error(op)(d1)(d2),
```

```
        (TIME ,REAL ) → d1 = d2 ∨ argtypes2-error(op)(d1)(d2),
        OTHERWISE → argtypes2-error(op)(d1)(d2)),
    MUL
    → (case hd(d1)
        (UNIVERSAL_INTEGER ,INTEGER ,REAL )
        → match-types(d1)(d2)∨ is-time-tdesc?(d2),
        TIME
        → is-integer-tdesc?(d2)∨ is-real-tdesc?(d2),
        OTHERWISE → argtypes2-error(op)(d1)(d2)),
    DIV
    → (case hd(d1)
        (UNIVERSAL_INTEGER ,INTEGER ,REAL )
        → match-types(d1)(d2)∨ argtypes2-error(op)(d1)(d2),
        TIME
        → is-integer-tdesc?(d2)∨ is-real-tdesc?(d2),
        OTHERWISE → argtypes2-error(op)(d1)(d2)),
    (MOD ,REM )
    → (case hd(d1)
        (UNIVERSAL_INTEGER ,INTEGER )
        → is-integer-tdesc?(d2)∨ argtypes2-error(op)(d1)(d2),
        OTHERWISE → argtypes2-error(op)(d1)(d2)),
    EXP
    → (case hd(d1)
        (UNIVERSAL_INTEGER ,INTEGER ,REAL )
        → is-integer-tdesc?(d2)∨ argtypes2-error(op)(d1)(d2),
        OTHERWISE → argtypes2-error(op)(d1)(d2)),
    CONCAT
    → (is-bit-tdesc?(d1)
       → is-bit-tdesc?(d2)∨ is-bitvector-tdesc?(d2),
       (is-bit-tdesc?(d2)
        → is-bit-tdesc?(d1)∨ is-bitvector-tdesc?(d1),
        (is-array-tdesc?(d1)∧ is-array-tdesc?(d2)
         → match-array-type-names(idf(d1),idf(d2))
                ∧ match-types(elty(d1),elty(d2)),
         argtypes2-error(op)(d1)(d2)))),
    (EQ ,NE ) → match-types(d1,d2)∨ argtypes2-error(op)(d1)(d2),
    (LT ,LE ,GT ,GE )
    → (is-scalar-tdesc?(d1)∧ is-scalar-tdesc?(d2)
       → match-types(d1)(d2)∨ argtypes2-error(op)(d1)(d2),
       is-bitvector-tdesc?(d1)∧ is-bitvector-tdesc?(d2)→ tt,
       argtypes2-error(op)(d1)(d2)),
    OTHERWISE → error(cat("Unrecognized Stage 3 VHDL operator: ")(op)))

argtypes2-error(op)(d1)(d2)
= error(cat("Operator ")(op)(" not implemented for pair of types: ")(d1)(d2))

restype2(binary-op)(d1,d2)(t)
= (case binary-op
    (AND ,NAND ,OR ,NOR ,XOR ,ADD ,SUB ,MOD ,REM ,EXP)
    → mk-type((DUMMY VAL) )(d1),
    MUL
    → (case hd(d1)
        (UNIVERSAL_INTEGER ,INTEGER ,REAL ) → mk-type((DUMMY VAL) )(d2),
        TIME → mk-type((DUMMY VAL) )(d1),
        OTHERWISE → error("Shouldn't happen!")),
    DIV
    → (case hd(d1)
```

```
        (UNIVERSAL_INTEGER ,INTEGER ,REAL ) → mk-type((DUMMY VAL) )(d2),
        TIME
        → (case hd(d2)
             (UNIVERSAL_INTEGER ,INTEGER ,REAL ) → mk-type((DUMMY VAL) )(d1),
             TIME → mk-type((DUMMY VAL) )(univint-type-desc(t)),
             OTHERWISE → error("Shouldn't happen!")),
        OTHERWISE → error("Shouldn't happen!")),
    CONCAT → mk-type((DUMMY VAL) )(mk-concat-tdesc(d1)(d2)(t)),
    OTHERWISE
    → error(cat("Unrecognized Stage 3 VHDL binary operator: ")(binary-op)))

mk-concat-tdesc(d1)(d2)(t)
= (is-bit-tdesc?(d1)∨ is-bitvector-tdesc?(d1)
   → array-type-desc
       (new-array-type-name(BIT_VECTOR ))(ε)(ε)(tt)(direction(d1))(lb(d1))(ε)
       (bit-type-desc(t)),
   let idf1 = idf(d1) in
    array-type-desc
      (new-array-type-name((consp(idf1)→ hd(idf1), idf1)))(ε)(ε)(tt)
      (direction(d1))(lb(d1))(ε)(elty(d1)))

resval2(d1,d2)(op)(e1,e2)
= (e1 = *UNDEF* ∨ e2 = *UNDEF* → *UNDEF* ,
   let tg = tag(d1) in
    (case tg
      *BOOL*
      → (case op
           AND → e1 ∧ e2,
           NAND → ¬(e1 ∧ e2),
           OR → e1 ∨ e2,
           NOR → ¬(e1 ∨ e2),
           XOR → (e1 = e2 → ff, tt),
           EQ → e1 = e2,
           NE → e1 ≠ e2,
           LT → ¬e1 ∧ e2,
           LE → ¬e1 ∨ e2,
           GT → e1 ∧ ¬e2,
           GE → e1 ∨ ¬e2,
           OTHERWISE
           → error
               (cat("Unrecognized Stage 3 VHDL 'boolean' binary operator: ")(op))),
      *BIT*
      → (case op
           AND
           → (e1 = 1 ∧ e2 = 1 → mk-bit-simp-symbol(1), mk-bit-simp-symbol(0)),
           NAND
           → (e1 = 0 ∨ e2 = 0 → mk-bit-simp-symbol(1), mk-bit-simp-symbol(0)),
           OR
           → (e1 = 1 ∨ e2 = 1 → mk-bit-simp-symbol(1), mk-bit-simp-symbol(0)),
           NOR
           → (e1 = 0 ∧ e2 = 0 → mk-bit-simp-symbol(1), mk-bit-simp-symbol(0)),
           XOR → (e1 = e2 → mk-bit-simp-symbol(0), mk-bit-simp-symbol(1)),
           EQ → e1 = e2,
           NE → e1 ≠ e2,
           LT → e1 = 0 ∧ e2 = 1,
           LE → e1 = 0 ∨ e2 = 1,
           GT → e1 = 1 ∧ e2 = 0,
```

```
        GE → e1 = 1 ∨ e2 = 0,
        OTHERWISE
        → error
            (cat("Unrecognized Stage 3 VHDL 'bit' binary operator: ")(op))),
    (*INT* ,*TIME* )
    → (case op
        ADD → e1+e2,
        SUB → e1−e2,
        MUL → e1×e2,
        DIV → (e2 = 0 → error("Illegal division by zero!"),
                e1/e2),
        MOD → mod(e1,e2),
        REM → rem(e1,e2),
        EXP → e1 ^ e2,
        EQ → e1 = e2,
        NE → e1 ≠ e2,
        LT → e1 < e2,
        LE → e1 ≤ e2,
        GT → e1 > e2,
        GE → e1 ≥ e2,
        OTHERWISE
        → error
            (cat("Unrecognized Stage 3 VHDL 'integer' binary operator: ")(op))),
    *REAL* → error(cat("Floating point operator not yet implemented: ")(op)),
    *ENUMTYPE*
    → (case op
        EQ → e1 = e2,
        NE → e1 ≠ e2,
        LT → enum-lt(e1)(e2)(literals(d1)),
        LE → enum-le(e1)(e2)(literals(d1)),
        GT → enum-lt(e2)(e1)(literals(d1)),
        GE → enum-le(e2)(e1)(literals(d1)),
        OTHERWISE
        → error
            (cat("Unrecognized Stage 3 VHDL 'enumeration type' binary operator: ")
             (op))),
    *ARRAYTYPE* → *UNDEF* ,
    OTHERWISE
    → error(cat("Unrecognized Stage 3 VHDL binary operator type: ")(tg))))

enum-lt(e1)(e2)(enum-lits)
= let e1pos = position(e1)(enum-lits)
      and e2pos = position(e2)(enum-lits) in
   e1pos < e2pos

enum-le(e1)(e2)(enum-lits)
= let e1pos = position(e1)(enum-lits)
      and e2pos = position(e2)(enum-lits) in
   e1pos ≤ e2pos
```

6.5.13 Primitive Semantic Equations

(N1) $\underline{\mathbf{N}}$ ⟦ constant ⟧ = constant

(B1) $\underline{\mathbf{B}}$ ⟦ bitlit ⟧ = bitlit

7 Interphase Abstract Syntax Tree Transformation

Owing to the relative simplicity of the Stage 1 VHDL language subset, Phases 1 and 2 of the Stage 1 VHDL translator were able to use the same abstract syntax.

Stage 2 VHDL was a considerably more sophisticated language subset. Consequently, it became convenient to allow Phase 2 of the VHDL translator for Stage 2 VHDL and subsequent stages — viz. Stage 3 VHDL — to employ a different abstract syntax for the language than does Phase 1, for reasons discussed below.

Accordingly, as the final act of Phase 1 translation of a given Stage 3 VHDL hardware description, an "interphase" *abstract syntax tree transformation* is performed that yields a new abstract syntax tree (AST) for use by Phase 2. This transformation does not modify the original AST. Although the resulting transformed AST may resemble the original in many respects, there will also be substantial differences.

We should recall that in Phase 1, when abstract syntax trees are occasionally injected into the TSE, it is their *transformed* versions that are used; this occurs with array type descriptors created by functions **process-slcdec** and **DT8**, subprogram descriptors created by function **process-subprog-body**, and ***SENS*** (sensitivity list) descriptors updated with new **refs** by function **SLT2**.

7.1 Interphase Semantic Functions

The abstract syntax tree transformation is carried out by principal semantic functions **DFX** (design files), **ENX** (entity declarations), **ARX** (architecture bodies), **PDX** (port declarations), **DX** (declarations), **CSX** (concurrent statements), **SLX** (sensitivity lists), **SSX** (sequential statements), **AX** (case alternatives), **DRX** (discrete ranges), **WX** (waveforms), **TRX** (transactions), **MEX** (reference lists), and **EX** and **RX** (expressions). These are assisted by several important auxiliary semantic functions, most notably the function **transform-name**.

Following Phase 1 construction of the tree-structured environment (TSE), semantic function **DFX** is applied to the original AST to initiate the transformation, which uses (but does not modify) the TSE. Once the AST transformation is complete, Phase 1 auxiliary semantic function **phase2** is invoked with the transformed AST and the TSE as syntactic and semantic arguments, respectively, to initiate Phase 2 translation (see Section 8).

Generally speaking, the AST-transforming semantic functions straightforwardly reconstruct their syntactic arguments from their transformed immediate syntactic constituents, with the following exceptions:

- transformation of `PORT` declarations into `SIGNAL` declarations
- "desugaring" of sensitivity lists in `PROCESS` statements:
  converting them into explicit final `WAIT` statements
- "desugaring" of concurrent signal assignment statements:

converting them into equivalent PROCESS statements

- "desugaring" of secondary units of physical type TIME:
  converting them into the base unit FS (*femtoseconds*)
- disambiguation of **ref**s as either array references or subprogram calls
- overload resolution between BOOLEAN and BIT operators
- overload resolution between INTEGER and REAL operators

7.2 Transformed Abstract Syntax of Names

An important case in point is the translation of names, e.g. **ref**s, which are heavily overloaded: the Phase 1 semantic function **name-type**, which checks them and determines their type, is necessarily complex. Given the identical abstract syntax, a Phase 2 semantic function for **ref**s would exhibit analogous complexity; instead, it was deemed preferable to transform the abstract syntax of **ref**s into a form more suitable for Phase 2.

Thus, the abstract syntax of **ref**s used in Phase 1 is:

```
 ref ::= REF name
name ::= id | name id | name expr*
```

while the abstract syntax of **ref**s used in Phase 2 is:

```
ref ::= REF basic-ref
basic-ref ::= modifier+
modifier  ::= SREF id+ id
            | INDEX expr
            | SELECTOR id
            | PARLIST expr*
```

Although not reflected in the syntax shown above, a **basic-ref** (basic reference) must begin with a *simple reference* **SREF id$^+$ id**, which has for convenience been classified with the *modifiers*. The **id** is the *root identifier*, and **id$^+$** is the *TSE access path* for this **ref**. The structures following this root basic reference are called *modifiers*. An **INDEX** modifier denotes an array reference, a **SELECTOR** modifier denotes a record field access (not used in Stage 3 VHDL), and a **PARLIST** modifier denotes a subprogram call. This linear arrangement of a simple reference followed by zero or more modifiers makes the translation of **ref**s in Phase 2 relatively straightforward, as the components of a **ref** are grouped from the left and thus a **ref** can be translated from left to right.

7.3 Interphase Semantic Equations

Most of the semantic equations for the interphase abstract syntax tree transformation, being straightforward, will be displayed without comment.

7.3.1 Stage 3 VHDL Design Files

(DFX1) **DFX** ⟦ **DESIGN-FILE** id pkg-decl* pkg-body* use-clause* ent-decl arch-body ⟧ (t)
= **let** $p_0 = \%(\epsilon)(id)$ **in**
(**DESIGN-FILE** ,id,**DX** ⟦ pkg-decl* ⟧ $(p_0)(t)$,**DX** ⟦ pkg-body* ⟧ $(p_0)(t)$,
DX ⟦ use-clause* ⟧ $(p_0)(t)$,**ENX** ⟦ ent-decl ⟧ $(p_0)(t)$,
ARX ⟦ arch-body ⟧ $(p_0)(t)$)

7.3.2 Entity Declarations

(ENX1) **ENX** ⟦ **ENTITY** id port-decl* decl* opt-id ⟧ (p)(t)
= insert-phase1-hook
((**ENTITY** ,id,**PDX** ⟦ port-decl* ⟧ (%(p)(id))(t),**DX** ⟦ decl* ⟧ (%(p)(id))(t),opt-id))
(ent-decl)

7.3.3 Architecture Bodies

(ARX1) **ARX** ⟦ **ARCHITECTURE** id_1 id_2 decl* con-stat* opt-id ⟧ (p)(t)
= **let** $p_1 = \%(\%(p)(id_2))(id_1)$ **in**
(**ARCHITECTURE** ,id_1,id_2,**DX** ⟦ decl* ⟧ $(p_1)(t)$,**CSX** ⟦ con-stat* ⟧ $(p_1)(t)$,opt-id)

7.3.4 Port Declarations

(PDX0) **PDX** ⟦ ε ⟧ (p)(t) = ε

(PDX1) **PDX** ⟦ port-decl port-decl* ⟧ (p)(t)
= cons(**PDX** ⟦ port-decl ⟧ (p)(t),**PDX** ⟦ port-decl* ⟧ (p)(t))

(PDX2) **PDX** ⟦ **DEC PORT** id^+ mode type-mark opt-expr ⟧ (p)(t)
= (**DEC** ,**SIG** ,id^+,type-mark,
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(PDX3) **PDX** ⟦ **SLCDEC PORT** id^+ mode slice-name opt-expr ⟧ (p)(t)
= (**SLCDEC** ,**SIG** ,id^+,
let (type-mark,discrete-range) = slice-name **in**
(type-mark,**DRX** ⟦ discrete-range ⟧ (p)(t)),
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

7.3.5 Declarations

(DX0) **DX** ⟦ ε ⟧ (p)(t) = ε

(DX1) **DX** ⟦ decl decl* ⟧ (p)(t) = cons(**DX** ⟦ decl ⟧ (p)(t),**DX** ⟦ decl* ⟧ (p)(t))

(DX2) **DX** ⟦ pkg-decl pkg-decl* ⟧ (p)(t)
= cons(**DX** ⟦ pkg-decl ⟧ (p)(t),**DX** ⟦ pkg-decl* ⟧ (p)(t))

(DX3) **DX** ⟦ pkg-body pkg-body* ⟧ (p)(t)
= cons(**DX** ⟦ pkg-body ⟧ (p)(t),**DX** ⟦ pkg-body* ⟧ (p)(t))

(DX4) **DX** ⟦ use-clause use-clause* ⟧ (p)(t)
= cons(**DX** ⟦ use-clause ⟧ (p)(t),**DX** ⟦ use-clause* ⟧ (p)(t))

(DX5) **DX** ⟦ **DEC** object-class id+ type-mark opt-expr ⟧ (p)(t)
= (**DEC** ,object-class,id+,type-mark,
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(DX6) **DX** ⟦ **SLCDEC** object-class id+ slice-name opt-expr ⟧ (p)(t)
= (**SLCDEC** ,object-class,id+,
let (type-mark,discrete-range) = slice-name **in**
(type-mark,**DRX** ⟦ discrete-range ⟧ (p)(t)),
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(DX7) **DX** ⟦ **ETDEC** id id+ ⟧ (p)(t) = (**ETDEC** ,id,id+)

(DX8) **DX** ⟦ **ATDEC** id discrete-range type-mark ⟧ (p)(t)
= (**ATDEC** ,id,**DRX** ⟦ discrete-range ⟧ (p)(t),type-mark)

(DX9) **DX** ⟦ **PACKAGE** id decl* opt-id ⟧ (p)(t)
= (**PACKAGE** ,id,**DX** ⟦ decl* ⟧ (%(p)(id))(t),opt-id)

(DX10) **DX** ⟦ **PACKAGEBODY** id decl* opt-id ⟧ (p)(t)
= **let** d = t(p)(id) **in**
let q = %(path(d))(id) **in**
(**PACKAGEBODY** ,id,**DX** ⟦ decl* ⟧ (q)(t),opt-id)

(DX11) **DX** ⟦ **PROCEDURE** id proc-par-spec* ⟧ (p)(t)
= **let** d = t(p)(id) **in**
(null(body(d))→ error(cat("Missing subprogram body: ")(namef
(d))),
(**PROCEDURE** ,id,proc-par-spec*))

(DX12) **DX** ⟦ **FUNCTION** id func-par-spec* type-mark ⟧ (p)(t)
= **let** d = t(p)(id) **in**
(null(body(d))→ error(cat("Missing subprogram body: ")(namef
(d))),
(**FUNCTION** ,id,func-par-spec*,type-mark))

(DX13) **DX** ⟦ **SUBPROGBODY** subprog-spec decl* seq-stat* opt-id ⟧ (p)(t)
= **let** (tg,id,par-spec*,type-mark) = subprog-spec **in**
let p_1 = %(p)(id) **in**
(**SUBPROGBODY** ,
let decl = subprog-spec **in**
DX ⟦ decl ⟧ (p)(t),**DX** ⟦ decl* ⟧ (p_1)(t),**SSX** ⟦ seq-stat* ⟧ (p_1)(t),opt-id)

(DX14) **DX** ⟦ **USE** dotted-name$^+$ ⟧ (p)(t) = (**USE** ,dotted-name$^+$)

(DX15) **DX** ⟦ **STDEC** id type-mark opt-discrete-range ⟧ (p)(t)
= (**STDEC** ,id,type-mark,
(null(opt-discrete-range)→ ε,
let (direction,expr$_1$,expr$_2$) = opt-discrete-range **in**
(direction,second(**EX** ⟦ expr$_1$ ⟧ (p)(t)),second(**EX** ⟦ expr$_2$ ⟧ (p)(t)))))

(DX16) **DX** ⟦ **ITDEC** id discrete-range ⟧ (p)(t)
= (**ITDEC** ,id,
let (direction,expr$_1$,expr$_2$) = discrete-range **in**
(direction,second(**EX** ⟦ expr$_1$ ⟧ (p)(t)),second(**EX** ⟦ expr$_2$ ⟧ (p)(t))))

7.3.6 Concurrent Statements

(CSX0) **CSX** ⟦ ε ⟧ (p)(t) = ε

(CSX1) **CSX** ⟦ con-stat con-stat* ⟧ (p)(t)
= cons(**CSX** ⟦ con-stat ⟧ (p)(t),**CSX** ⟦ con-stat* ⟧ (p)(t))

(CSX2) **CSX** ⟦ **PROCESS** id ref* decl* seq-stat* opt-id ⟧ (p)(t)
= **let** p$_1$ = %(p)(id) **in**
(**PROCESS** ,id,**DX** ⟦ decl* ⟧ (p$_1$)(t),
let seq-stat$_1^*$ = (null(seq-stat*)
→ ((**WAIT** ,(**AT** ,mk-atmark()),ref*,ε,ε)),
(null(ref*)→ seq-stat*,
append
(seq-stat*,
((**WAIT** ,(**AT** ,mk-atmark()),ref*,ε,ε))))) **in**
SSX ⟦ seq-stat$_1^*$ ⟧ (p$_1$)(t),opt-id)

(CSX3) **CSX** ⟦ **SEL-SIGASSN** atmark delay-type id expr ref selected-waveform$^+$ ⟧ (p)(t)
= **let** expr* = cons(expr,
collect-expressions-from-selected-waveforms
(selected-waveform$^+$)) **in**
let ref* = delete-duplicates
(collect-signals-from-expr-list(expr*)(t)(p)(ε)) **in**
let case-alt$^+$ = construct-case-alternatives
(ref)(delay-type)(selected-waveform$^+$) **in**
let case-stat = (**CASE** ,atmark,expr,case-alt$^+$) **in**
let process-stat = (**PROCESS** ,id,ref*,ε,(case-stat),id) **in**
insert-phase1-hook(**CSX** ⟦ process-stat ⟧ (p)(t))(con-stat)

(CSX4) **CSX** ⟦ **COND-SIGASSN** atmark delay-type id ref cond-waveform* waveform ⟧ (p)(t)
= **let** expr* = nconc
(collect-expressions-from-conditional-waveforms
(cond-waveform*),
collect-transaction-expressions(second(waveform))) **in**
let ref* = delete-duplicates
(collect-signals-from-expr-list(expr*)(t)(p)(ε)) **in**
(null(cond-waveform*)
→ **let** sig-assn-stat = (**SIGASSN** ,atmark,delay-type,ref,waveform) **in**
let process-stat = (**PROCESS** ,id,ref*,ε,(sig-assn-stat),id) **in**

insert-phase1-hook(**CSX** ⟦ process-stat ⟧ (p)(t))(con-stat),
let cond-part$^+$ = construct-cond-parts
(ref)(delay-type)(cond-waveform*)
and else-part = ((**SIGASSN** ,(**AT** ,mk-atmark()),delay-type,ref,waveform)) **in**
let if-stat = (**IF** ,atmark,cond-part$^+$,else-part) **in**
let process-stat = (**PROCESS** ,id,ref*,ϵ,(if-stat),id) **in**
insert-phase1-hook(**CSX** ⟦ process-stat ⟧ (p)(t))(con-stat))

7.3.7 Sensitivity Lists

(SLX0) **SLX** ⟦ ϵ ⟧ (p)(t) = ϵ

(SLX1) **SLX** ⟦ ref ref* ⟧ (p)(t) = cons(**SLX** ⟦ ref ⟧ (p)(t),**SLX** ⟦ ref* ⟧ (p)(t))

(SLX2) **SLX** ⟦ **REF** name ⟧ (p)(t)
= **let** expr = ref **in**
second(**EX** ⟦ expr ⟧ (p)(t))

7.3.8 Sequential Statements

(SSX1) **SSX** ⟦ seq-stat seq-stat* ⟧ (p)(t)
= cons(**SSX** ⟦ seq-stat ⟧ (p)(t),**SSX** ⟦ seq-stat* ⟧ (p)(t))

(SSX2) **SSX** ⟦ **NULL** atmark ⟧ (p)(t) = (**NULL** ,atmark)

(SSX3) **SSX** ⟦ **VARASSN** atmark ref expr ⟧ (p)(t)
= (**VARASSN** ,atmark,
let expr$_0$ = ref **in**
second(**EX** ⟦ expr$_0$ ⟧ (p)(t)),second(**EX** ⟦ expr ⟧ (p)(t)))

(SSX4) **SSX** ⟦ **SIGASSN** atmark delay-type ref waveform ⟧ (p)(t)
= (**SIGASSN** ,atmark,delay-type,
let expr = ref **in**
second(**EX** ⟦ expr ⟧ (p)(t)),**WX** ⟦ waveform ⟧ (p)(t))

(SSX5) **SSX** ⟦ **IF** atmark cond-part$^+$ else-part ⟧ (p)(t)
= **let** seq-stat* = else-part **in**
(**IF** ,atmark,transform-if(cond-part$^+$)(p)(t),**SSX** ⟦ seq-stat* ⟧ (p)(t))

transform-if(cond-part*)(p)(t)
= (null(cond-part*)→ ϵ,
let (expr,seq-stat*) = hd(cond-part*) **in**
cons((second(**EX** ⟦ expr ⟧ (p)(t)),**SSX** ⟦ seq-stat* ⟧ (p)(t)),
transform-if(tl(cond-part*))(p)(t)))

(SSX6) **SSX** ⟦ **CASE** atmark expr case-alt$^+$ ⟧ (p)(t)
= (**CASE** ,atmark,second(**EX** ⟦ expr ⟧ (p)(t)),**AX** ⟦ case-alt$^+$ ⟧ (p)(t))

(SSX7) **SSX** ⟦ **LOOP** atmark id seq-stat* opt-id ⟧ (p)(t)
= (**LOOP** ,atmark,id,**SSX** ⟦ seq-stat* ⟧ (%(p)(id))(t),opt-id)

(SSX8) **SSX** ⟦ **WHILE** atmark id expr seq-stat* opt-id ⟧ (p)(t)
= (**WHILE** ,atmark,id,second(**EX** ⟦ expr ⟧ (%(p)(id))(t)),
SSX ⟦ seq-stat* ⟧ (%(p)(id))(t),opt-id)

(SSX9) **SSX** ⟦ **FOR** atmark id ref discrete-range seq-stat* opt-id ⟧ (p)(t)
= (**FOR** ,atmark,id,second(**EX** ⟦ ref ⟧ (%(p)(id))(t)),
DRX ⟦ discrete-range ⟧ (%(p)(id))(t),**SSX** ⟦ seq-stat* ⟧ (%(p)(id))(t),opt-id)

(SSX10) **SSX** ⟦ **EXIT** atmark opt-dotted-name opt-expr ⟧ (p)(t)
= (**EXIT** ,atmark,opt-dotted-name,
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(SSX11) **SSX** ⟦ **CALL** atmark ref ⟧ (p)(t)
= (**CALL** ,atmark,
let expr = ref **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(SSX12) **SSX** ⟦ **RETURN** atmark opt-expr ⟧ (p)(t)
= (**RETURN** ,atmark,
let expr = opt-expr **in**
second(**EX** ⟦ expr ⟧ (p)(t)))

(SSX13) **SSX** ⟦ **WAIT** atmark ref* opt-expr$_1$ opt-expr$_2$ ⟧ (p)(t)
= **let** expr$_1$ = opt-expr$_1$
and expr$_2$ = opt-expr$_2$ **in**
(**WAIT** ,atmark,**MEX** ⟦ ref* ⟧ (p)(t),second(**EX** ⟦ expr$_1$ ⟧ (p)(t)),
second(**EX** ⟦ expr$_2$ ⟧ (p)(t)))

7.3.9 Case Alternatives

(AX0) **AX** ⟦ ε ⟧ (p)(t) = ε

(AX1) **AX** ⟦ case-alt case-alt* ⟧ (p)(t)
= cons(**AX** ⟦ case-alt ⟧ (p)(t),**AX** ⟦ case-alt* ⟧ (p)(t))

(AX2) **AX** ⟦ **CASECHOICE** discrete-range$^+$ seq-stat* ⟧ (p)(t)
= (**CASECHOICE** ,**DRX** ⟦ discrete-range$^+$ ⟧ (p)(t),**SSX** ⟦ seq-stat* ⟧ (p)(t))

(AX3) **AX** ⟦ **CASEOTHERS** seq-stat* ⟧ (p)(t) = (**CASEOTHERS** ,**SSX** ⟦ seq-stat* ⟧ (p)(t))

7.3.10 Discrete Ranges

(DRX0) **DRX** ⟦ ε ⟧ (p)(t) = ε

(DRX1) **DRX** ⟦ discrete-range discrete-range* ⟧ (p)(t)
= cons(**DRX** ⟦ discrete-range ⟧ (p)(t),**DRX** ⟦ discrete-range* ⟧ (p)(t))

(DRX2) **DRX** ⟦ discrete-range ⟧ (p)(t)
= **let** (direction,expr$_1$,expr$_2$) = discrete-range **in**
(direction,second(**EX** ⟦ expr$_1$ ⟧ (p)(t)),second(**EX** ⟦ expr$_2$ ⟧ (p)(t)))

7.3.11 Waveforms and Transactions

(WX1) $\underline{\mathbf{WX}}$ ⟦ **WAVE** transaction$^+$ ⟧ (p)(t) = (**WAVE** ,$\underline{\mathbf{TRX}}$ ⟦ transaction$^+$ ⟧ (p)(t))

(TRX1) $\underline{\mathbf{TRX}}$ ⟦ transaction transaction* ⟧ (p)(t)
= (null(transaction*)→ ($\underline{\mathbf{TRX}}$ ⟦ transaction ⟧ (p)(t)),
let transaction$_1^+$ = transaction* **in**
cons($\underline{\mathbf{TRX}}$ ⟦ transaction ⟧ (p)(t),$\underline{\mathbf{TRX}}$ ⟦ transaction$_1^+$ ⟧ (p)(t)))

(TRX2) $\underline{\mathbf{TRX}}$ ⟦ **TRANS** expr opt-expr ⟧ (p)(t)
= (**TRANS** ,second($\underline{\mathbf{EX}}$ ⟦ expr ⟧ (p)(t)),
let expr$_1$ = opt-expr **in**
second($\underline{\mathbf{EX}}$ ⟦ expr$_1$ ⟧ (p)(t)))

7.3.12 Expressions

(MEX0) $\underline{\mathbf{MEX}}$ ⟦ ϵ ⟧ (p)(t) = ϵ

(MEX1) $\underline{\mathbf{MEX}}$ ⟦ ref ref* ⟧ (p)(t) = cons(second($\underline{\mathbf{EX}}$ ⟦ ref ⟧ (p)(t)),$\underline{\mathbf{MEX}}$ ⟦ ref* ⟧ (p)(t))

(EX0) $\underline{\mathbf{EX}}$ ⟦ ϵ ⟧ (p)(t) = (void-type-desc(t),ϵ)

(EX1) $\underline{\mathbf{EX}}$ ⟦ **FALSE** ⟧ (p)(t) = (bool-type-desc(t),(**FALSE**))

(EX2) $\underline{\mathbf{EX}}$ ⟦ **TRUE** ⟧ (p)(t) = (bool-type-desc(t),(**TRUE**))

(EX3) $\underline{\mathbf{EX}}$ ⟦ **BIT** bitlit ⟧ (p)(t) = (bit-type-desc(t),(**BIT** ,bitlit))

(EX4) $\underline{\mathbf{EX}}$ ⟦ **NUM** constant ⟧ (p)(t) = (int-type-desc(t),(**NUM** ,constant))

(EX5) $\underline{\mathbf{EX}}$ ⟦ **TIME** constant time-unit ⟧ (p)(t)
= **let** normalized-constant = (case time-unit
FS → $\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
PS → 1000×$\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
NS → 1000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
US → 1000000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
MS → 1000000000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
SEC → 1000000000000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧ ,
MIN → 60×(1000000000000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧),
HR → 3600×(1000000000000000×$\underline{\mathbf{N}}$ ⟦ constant ⟧),
OTHERWISE
→ error
(cat("Illegal unit name for physical type TIME: ")
(time-unit))) **in**
(time-type-desc(t),(**TIME** ,normalized-constant,**FS**))

(EX6) $\underline{\mathbf{EX}}$ ⟦ **CHAR** constant ⟧ (p)(t)
= **let** d = lookup(t)((**STANDARD**))(expr) **in**
(type(d),(**CHAR** ,constant))

(EX7) $\underline{\mathbf{EX}}$ ⟦ **BITSTR** bit-lit* ⟧ (p)(t) = (ϵ,(**BITSTR** ,bit-lit*))

(EX8) $\underline{\mathbf{EX}}$ ⟦ **STR** char-lit* ⟧ (p)(t) = (ϵ,(**STR** ,char-lit*))

(EX9) $\underline{\mathbf{EX}}$ ⟦ **REF** name ⟧ (p)(t) = transform-name(name)(ϵ)(ϵ)(p)(t)

```
transform-name(name)(w)(ast*0)(p)(t)
= (null(w)
   → let w1 = lookup2(t)(p)(ε)(hd(name)) in
       (w1 = *UNBOUND* → error(cat("Unbound identifier: ")($(p)(hd(name)))),
        (second(tmode(w1))= TYP → transform-name(tl(name))(w1)(ε)(p)(t),
         transform-name
           (tl(name))(w1)(((SREF ,path(tdesc(w1)),idf(tdesc(w1)))))(p)(t))),
   let d = tdesc(w)
       and tm = tmode(w) in
    let tg = tag(d) in
     (null(name)
      → (second(tm)= TYP → transform-name-aux(*CONVERSION* )(d)(ast*0),
          transform-name-aux(tg)(d)(ast*0)),
       let x = hd(name) in
        (consp(x)
         → let ast*1 = transform-list(x)(p)(t) in
             (second(tm)= TYP
              → transform-name
                   (tl(name))(w)((TYPECONV ,hd(ast*1),%(path(d))(idf(d))))(p)(t),
              second(tm)= OBJ ∧ is-array-tdesc?(d)
              → transform-name
                   (tl(name))((tm,elty(d)))
                   (nconc(ast*0,((INDEX ,hd(ast*1)))))(p)(t),
              (second(tm)= OBJ ∧ is-array?(type(d)))
                        ∨ (second(tm)∈ (REF VAL) ∧ is-array-tdesc?(d))
              → transform-name
                   (tl(name))
                   ((second(tm)= OBJ
                     → mk-type(tmode(type(d)))(elty(tdesc(type(d)))),
                     mk-type(tm)(elty(d))))
                   (nconc(ast*0,((INDEX ,hd(ast*1)))))(p)(t),
              transform-name
                 (tl(name))(extract-rtype(d))
                 (nconc(ast*0,((PARLIST ,ast*1))))(p)(t)),
          ((second(tm)= OBJ ∧ is-record?(type(d)))
                   ∨ (second(tm)∈ (REF VAL) ∧ is-record-tdesc?(d))
           → let d1 = (second(tm)= OBJ → tdesc(type(d)), d) in
               let d2 = lookup-record-field(components(d1))(x) in
                transform-name
                  (tl(name))(mk-type(tm)(d2))(nconc(ast*0,((SELECTOR ,x))))
                  (p)(t),
           second(tm)= OBJ ∧ is-record-tdesc?(d)
           → let d2 = lookup-record-field(components(d))(x) in
                transform-name
                  (tl(name))(mk-type(tm)(d2))(nconc(ast*0,((SELECTOR ,x))))
                  (p)(t),
           let w1 = lookup-local(x)(%(path(d))(idf(d)))(p)(t) in
            (w1 = *UNBOUND*
             → error(cat("Unknown identifier: ")($(%(path(d))(idf(d)))(x))),
             transform-name
               (tl(name))(w1)(((SREF ,path(tdesc(w1)),idf(tdesc(w1)))))(p)
               (t))))))

transform-name-aux(tg)(d)(ast)
= (case tg
     *OBJECT* → (second(type(d)),(REF ,ast)),
     *ENUMELT* → (second(type(d)),(ENUMLIT ,idf(d))),
```

```
      (*PROCEDURE* ,*FUNCTION* )
      → (second(rtype(hd(signatures(d)))),
          (REF ,nconc(ast,((PARLIST ,ε))))),
      *CONVERSION* → (d,ast),
      *PACKAGE* → (d,(REF ,ast)),
      OTHERWISE → (d,(REF ,ast)))

transform-list(x)(p)(t)
= (null(x)→ ε,
    let expr = hd(x) in
     cons(second(EX [[ expr ]] (p)(t)),transform-list(tl(x))(p)(t)))
```

The functions **transform-name**, **transform-name-aux**, and **transform-list** produce the linear form of the basic references discussed above.

```
(EX10) EX [[ PAGGR expr* ]] (p)(t)
       = (length(expr*)= 1
          → let expr = hd(expr*) in
              EX [[ expr ]] (p)(t),
          (ε,(PAGGR ,ex-paggr(expr*)(p)(t))))


(EX11) EX [[ unary-op expr ]] (p)(t)
       = let (d,e) = EX [[ expr ]] (p)(t) in
          (case unary-op
             PLUS → (d,e),
             NOT → (d,(scalar-op(unary-op)(d),e)),
             NEG → (d,(scalar-op(unary-op)(d),e)),
             ABS → (d,(scalar-op(unary-op)(d),e)),
             OTHERWISE
             → error
                  (cat("Unrecognized Stage 3 VHDL unary operator: ")(unary-op)))

(EX12) EX [[ binary-op expr1 expr2 ]] (p)(t)
       = let (d1,e1) = EX [[ expr1 ]] (p)(t) in
           let (d2,e2) = EX [[ expr2 ]] (p)(t) in
            (d1,(scalar-op(binary-op)(d1),e1,e2))

(EX13) EX [[ relational-op expr1 expr2 ]] (p)(t)
       = let (d1,e1) = EX [[ expr1 ]] (p)(t) in
           let (d2,e2) = EX [[ expr2 ]] (p)(t) in
            (bool-type-desc(t),(scalar-op(relational-op)(d1),e1,e2))

scalar-op(op)(d)
= (is-bit-tdesc?(d)∨ is-bitvector-tdesc?(d)→ bits-op(op),
   is-real-tdesc?(d)→ real-op(op),
   op)

bits-op(op)
= (case op
     EQ → EQ ,
     NE → NE ,
     LT → LT ,
     LE → LE ,
     GT → GT ,
     GE → GE ,
```

NOT → **BNOT** ,
AND → **BAND** ,
NAND → **BNAND** ,
OR → **BOR** ,
NOR → **BNOR** ,
XOR → **BXOR** ,
OTHERWISE → error(cat(Undefined bitwise operator:)(op)))

real-op(op)
= (case op
EQ → **EQ** ,
NE → **NE** ,
LT → **RLT** ,
LE → **RLE** ,
GT → **RGT** ,
GE → **RGE** ,
NEG → **RNEG** ,
ABS → **RABS** ,
ADD → **RPLUS** ,
SUB → **RMINUS** ,
MUL → **RTIMES** ,
DIV → **RDIV** ,
EXP → **REXPT** ,
OTHERWISE → error(cat(Undefined 'real' operator:)(op)))

The functions **scalar-op**, **bits-op**, and **real-op** do overload resolution between `INTEGER`, `BIT`, and `REAL` operators.

(RX1) **RX** ⟦ expr ⟧ (p)(t) = **EX** ⟦ expr ⟧ (p)(t)

8 Phase 2: State Delta Generation

If Phase 1 of the Stage 3 VHDL translator completes without error, then after the interphase abstract syntax tree transformation has been accomplished (see Section 7), Phase 2, state delta generation, can proceed. Several kinds of checks have already been performed on the hardware description in Phase 1, the most significant being the detection of missing prior declarations of items such as variables and labels, the improper use of names, and static type checking. Thus, these checks do not have to be duplicated in Phase 2.

Phase 2 receives from Phase 1 the transformed abstract syntax tree (AST) for the hardware description, together with the tree-structured environment (TSE) — a complete record of the name/attribute associations corresponding to the hardware description's declarations and whose structure reflects that of the description. The TSE remains *fixed* throughout Phase 2. It contains all definitions needed to execute its corresponding Stage 3 VHDL hardware description, and Phase 1 has ensured that only that portion of the TSE visible at any given textual point of the description can be accessed during Phase 2. With the aid of the TSE, Phase 2 incrementally generates SDVS Simplifier assertions and state deltas.

8.1 Phase 2 Semantic Domains and Functions

The formal description of Phase 2 translation consists of *semantic domains* and *semantic functions*, the latter being functions from syntactic to semantic domains. *Compound semantic domains* are defined in terms of *primitive semantic domains*. Similarly, *primitive semantic functions* are unspecified (their definitions being understood implicitly) and the remaining semantic functions are defined (by syntactic cases) via *semantic equations*.

The principal Phase 2 semantic functions (and corresponding Stage 3 VHDL language constructs to which they assign meanings) are: **DF** (design files), **EN** (entity declarations), **AR** (architecture bodies), **D** (declarations), **CS** (concurrent statements), **SS** (sequential statements), **W** (waveforms), **TRM** and **TR** (transactions), **ME** and **MR** (expression lists), **E** and **R** (expressions), **T** (expression types), **B** (bit literals), and **N** (numeric literals).

Each of the principal semantic functions requires an appropriate *syntactic argument* — an abstract syntactic object (tree) produced by the interphase abstract syntax tree transformation (see Section 7). Most of the semantic functions take (at least) the following additional arguments:

- the *tree-structured environment (TSE)* generated in Phase 1;
- a *path*, indicating the currently "visible" portion of the TSE;
- a *continuation*, specifying which Phase 2 semantic function to invoke next;
- a *universe structure*; and
- an *execution stack*.

In the absence of errors, the Phase 2 semantic functions return a *list* of Simplifier assertions and state deltas. Moreover, **E** and **R** also return a translated expression and list of guard formulas. Guard formulas are inserted in the precondition of generated state deltas to ensure that certain conditions are met in the proof in which the state deltas appear. For example, if an array name is indexed by an expression, then Phase 2 generates a guard formula asserting that the index value is not out of range.

The *execution state* manipulated by Phase 2 translation involves two components: a *universe structure* (see Section 8.2.2) and an *execution stack* (see Section 8.2.3). An analogy with conventional denotational semantics can be applied: the execution state corresponds to the store, translated expressions and guard formulas correspond to expression values, and state delta/assertion lists correspond to non-error final answers.

When state deltas are generated by a semantic function, the continuation that is input to that function plays a slightly unconventional role: the result of applying to an execution state the continuation, or other continuations derived from the continuation, is appended to the postconditions of the generated state deltas. In the absence of errors, the item appended represents a list of state deltas. Such a continuation is evaluated and applied only when the state delta in whose postcondition it appears is applied.

For example, an `IF` statement having no `ELSE` part generates two state deltas: one for the case in which its condition evaluates to true, the other for the false case. The continuation for the true case represents the execution of the body of the `IF` statement succeeded by the execution of the statement following the `IF` statement. The continuation for the false case skips the body, and proceeds directly to the statement following the `IF` statement. Whichever of these two state deltas is applied determines which continuation is evaluated and applied to an execution state, and therefore which additional state deltas are subsequently generated.

8.1.1 Phase 2 Semantic Domains

The semantic domains and function types for Phase 2 of the Stage 3 VHDL translator are as follows.

Primitive Semantic Domains

Bool = {**FALSE**, **TRUE**}	Simplifier propositional (boolean) constants
Bit = {(**BS 0 1**), (**BS 1 1**)}	Simplifier bit constants (length 1 bitstrings)
Char = {(**CHAR 0**), ..., (**CHAR 127**)}	Simplifier character constants
n : **N** = {0, 1, 2, ...}	Simplifier natural number constants
id : **Id**	identifiers
SysId	system-generated identifiers (disjoint from **Id**)
t : **TEnv**	tree-structured environments (TSEs)
d : **Desc**	descriptors (see Section 6.2)
v : **UStruct**	universe structures (see Section 8.2.2)

stk : Stk	execution stacks (see Section 8.2.3)
e : TExpr	translated expressions
trans : TTrans	translated transactions
f, guard : GForm	lists of guard formulas
sd : SD	state deltas
Assert	SDVS Simplifier assertions
Error	error messages

Compound Semantic Domains

elbl : Elbl = Id + SysId	TSE edge labels
p, q: Path = Elbl*	TSE paths
qname: Name = Elbl (. Elbl)*	qualified names
d : Dv = Desc	denotable values (descriptors)
r : Env = Id → (Dv + {*UNBOUND*})	environments
Tmode = {PATH} × Id* + ({CONST, VAR, SIG, DUMMY} × {VAL, OUT, REF, OBJ, ACC, TYP})	type modes
w : Type = Tmode × Desc	types
u : Dc = UStruct → Stk → Ans	declaration & concurrent statement continuations
c : Sc = Dc	sequential statement continuations
k : Ec = (TExpr × GForm) → Sc	expression continuations
h : Mc = (TExpr* × GForm*) → Sc	expression list continuations
wave-cont : Wc = (TTrans* × GForm*) → Sc	waveform continuations
trans-cont : Tc = (TTrans × GForm) → Sc	transaction continuations
Ans = (SD + Assert)* + Error	final answers

8.1.2 Phase 2 Semantic Functions

The semantic functions for Phase 2 of the Stage 3 VHDL translator are as follows.

DF :	**Design → TEnv → Ans**	design file dynamic semantics
EN :	**Ent → TEnv → Path → Dc → Dc**	entity declaration dynamic semantics
AR :	**Arch → TEnv → Path → Dc → Dc**	architecture body dynamic semantics
D :	**Dec* → TEnv → Path → Dc → Dc**	declaration dynamic semantics

CS :	**CStat*** → **TEnv** → **Path** → **Dc** → **Dc**	concurrent statement dynamic semantics
SS :	**SStat*** → **TEnv** → **Path** → **Sc** → **Sc**	sequential statement dynamic semantics
W :	**Wave** → **TEnv** → **Path** → **Wc** → **Sc**	waveform dynamic semantics
TRM :	**Trans*** → **TEnv** → **Path** → **Wc** → **Sc**	transaction list dynamic semantics
TR :	**Trans** → **TEnv** → **Path** → **Tc** → **Sc**	transaction dynamic semantics
ME :	**Expr*** → **TEnv** → **Path** → **Mc** → **Sc**	expression list dynamic semantics (*l-values*)
MR :	**Expr*** → **TEnv** → **Path** → **Mc** → **Sc**	expression list dynamic semantics (*r-values*)
E :	**Expr** → **TEnv** → **Path** → **Ec** → **Sc**	expression dynamic semantics (*l-values*)
R :	**Expr** → **TEnv** → **Path** → **Ec** → **Sc**	expression dynamic semantics (*r-values*)
T :	**Expr** → **TEnv** → **Path** → **Desc**	expression types
B :	**BitLit** → **Bit**	bit values of bit literals (primitive)
N :	**NumLit** → **N**	integer values of numeric literals (primitive)

8.2 Phase 2 Execution State

As mentioned in Section 8.1, the *execution state* manipulated by Phase 2 translation consists of a *universe structure* and an *execution stack*. The purpose of this section is to elucidate the nature and role of these aspects of the execution state.

8.2.1 Unique Name Qualification

Except for quantification, the language of state deltas has no scoping, i.e., it is "flat." Even with quantification, the state deltas generated by the Stage 3 VHDL translator certainly do not have a scoping structure that naturally parallels the scopes of their corresponding Stage 3 VHDL hardware description. Furthermore, even if there were such a correspondence between source (Stage 3 VHDL) and target (state deltas) scopes, it would still be convenient to generate unique names for the SDVS user to use in proofs.

For example, a `PROCESS` statement may contain a declaration of a variable **x** of the same name as a signal in the enclosing architecture body. The inner instance of **x** can be distinguished from the outer instance by prefixing or *qualifying* it with the name (user-supplied or system-generated) of the process in which the inner instance is declared. We shall call such a qualified name, derived from the *static* structure of the Stage 3 VHDL hardware description, a *statically uniquely qualified name* or *SUQN*. At the beginning of Phase 2 translation (after the interphase AST transformation — see Section 7), the SUQN of any object (for which such a name makes sense) is recorded in the **qid** field associated with the object in the TSE.

Another important kind of unique name qualification is based on the *dynamic* execution of a Stage 3 VHDL description. A program unit can be reentered, either by repetition or recursion, and local declarations in the reentered program will be re-elaborated, creating new dynamic instances of entities that cannot be distinguished on the basis of static program structure. In this case new names that are distinct dynamic instances of the same statically uniquely qualified name are sufficient to enable the SDVS user to distinguish all instances of names for use in proofs. The separate dynamic instances of a name are indicated by appending **!n** to it, where **n** is a *dynamic instance index* for that name (e.g. **a.x**, **a.x!2**, **a.x!3**, ..., where **a.x!1** is simply denoted **a.x**). These names are called *dynamically uniquely qualified names* (DUQNs).

Only statically and dynamically uniquely qualified names appear in the state deltas generated by Phase 2 translation.

8.2.2 Universe Structure for Unique Dynamic Naming

Given that there may be several dynamic instances of the same SUQN in a Stage 3 VHDL hardware description, Phase 2 translation employs a mechanism called a *universe structure* (together with functions that access and manipulate it) to manage the creation of new dynamic instances of each distinct SUQN, as well as to ensure that the correct dynamic instance of each SUQN is available at any given time.

A **universe structure** consists of four components:

universe name :
The name of the current universe. A universe name has the form **z\u\n**, where **z** is the name of the main program and **n** is the current universe's ordinal number (**n** = 1, 2, ...).

universe counter :
The current universe's ordinal number.

universe stack :
A stack of universe names used to save and restore prior universes in accordance with the changes of environment in a Stage 3 VHDL hardware description.

universe variables :
The current universe's environment of statically and dynamically uniquely qualified names. This is a list of entries of the form **(SUQN, ordinal-number, ordinal-stack)**, one for each distinct SUQN. The ordinal number denotes the most recently created dynamic instance of that SUQN. The ordinal stack is a stack of this SUQN's ordinal numbers, whose top element denotes the current dynamic instance of this SUQN. This stack is used to save and restore prior dynamic instances of this SUQN in accordance with the changes of environment in a Stage 3 VHDL hardware description.

```
mk-initial-universe(z)
= let uname = catenate(z,"\u",1) in
    make-universe-data(uname,1,(uname),((z,1,(1))))

make-universe-data(uname,ucounter,ustack,uvars)
= (uname,ucounter,ustack,uvars)

universe-name(v) = hd(v)

universe-counter(v) = second(v)

universe-stack(v) = third(v)

universe-vars(v) = fourth(v)

push-universe(v,z,suqn*)
= let ucounter = 1+universe-counter(v) in
    let uname = catenate(z,"\u",ucounter) in
     let ustack = cons(uname,universe-stack(v)) in
      make-universe-data
        (uname,ucounter,ustack,push-universe-vars(suqn*,universe-vars(v)))

push-universe-vars(suqn*,vars)
= (null(suqn*)→ vars,
   let suqn = hd(suqn*) in
    let v = assoc(suqn,vars) in
     (null(v)→ push-universe-vars(tl(suqn*),cons(init-var(suqn),vars)),
      push-universe-vars(tl(suqn*),cons(push-var(v),vars))))
```

```
push-var(v)
= let n = next-var(second(v)) in
    (hd(v),n,cons(n,third(v)))

next-var(n)
= (numberp(n)→ n+1,
   (symbolp(n)→ mk-exp2(ADD ,n,1),
    let m = third(n) in
     (numberp(m)→ mk-exp2(ADD ,second(n),m+1),
      mk-exp2(ADD ,second(n),mk-exp2(ADD ,m,1)))))

init-var(suqn) = (suqn,1,(1))

pop-universe(v)(suqn*)
= let ustack = tl(universe-stack(v)) in
    let uname = hd(ustack) in
     make-universe-data
        (uname,universe-counter(v),ustack,
        pop-universe-vars(suqn*)(universe-vars(v)))

pop-universe-vars(suqn*,vars)
= (null(suqn*)→ vars,
   let suqn = hd(suqn*) in
    let v = assoc(suqn,vars) in
     pop-universe-vars(tl(suqn*),cons(pop-var(v),vars)))

pop-var(v) = (hd(v),second(v),tl(third(v)))

get-qualified-ids(suqn*)(v)
= (null(suqn*)→ ε,
   cons(qualified-id(hd(suqn*))(v),get-qualified-ids(tl(suqn*))(v)))

qualified-id(suqn)(v)
= let vars = universe-vars(v) in
    let suqn-triple = assoc(suqn,vars) in
     (suqn-triple
      → let n = hd(third(suqn-triple)) in
          name-qualified-id(suqn)(n),
      name-qualified-id(suqn)(1))

name-qualified-id(suqn)(n)
= (new-declarations()→ (PLACELEMENT ,suqn,n),
   (n = 1 → suqn, catenate(suqn,"!",n)))
```

Currently, the only part of the universe structure that is actually used for dynamic name qualification is the *universe variables* component. Each time a program unit that may have a declarative part (packages, entities, architectures, processes, subprogram bodies) is entered, the current universe is saved and an updated universe structure is created by **push-universe**. The universe structure's counter (ordinal) is incremented by one, a corresponding new universe name is created, and the old universe name is pushed onto the universe stack. In the universe variables component of the universe structure, the triple for each SUQN corresponding to each name declared in the unit's declarative part (except types) is updated: the value of its ordinal is incremented by one and this new ordinal value is pushed onto the ordinal stack of the SUQN's triple. Whenever any SUQN needs to be dynamically uniquely

qualified, the top element of its ordinal stack is used to find the index of the current dynamic instance of that SUQN.

When such a program unit is exited, **pop-universe** restores the universe name by popping it from the universe stack. The ordinal stack of the triple of the SUQN of each (non-type) name declared in this unit is popped, restoring the current dynamic qualification of that SUQN to a former value.

The functions **get-qualified-ids**, **qualified-id**, and **name-qualified-id** accomplish the dynamic qualification of SUQNs relative to a universe structure.

8.2.3 Execution Stack

The elements of the *execution stack* are descriptors that contain information to control normal returns and exits from program units, as well as the undeclaration of objects, packages, subprograms, and formal parameters.

There are several kinds of execution stack descriptors, and more detailed explanations of their roles will be provided at the points in the semantics where they are used. For now, we note that each descriptor has four components: an identifying *tag*; an *identifier*, *identifier sequence*, or *fully qualified name* that associates the descriptor with some program unit; a *path* that may replace the current path to effect a change of environment; and a *function*, which may be a *continuation* or *continuation transformer*, that will effect a change of control and environment corresponding to the descriptor's purpose.

stack bottom :

$$< \textbf{*STKBOTTOM*}, \textbf{id}, \epsilon, \epsilon >$$

This descriptor is the execution stack "bottom marker," used to terminate model execution and to prevent execution stack underflow. The identifier **id** is the name of the Stage 3 VHDL design file.

package body exit :

$$< \textbf{*PACKAGE-BODY-EXIT*}, \textbf{id}, \textbf{p}, \textbf{u} >$$

This descriptor is pushed onto the execution stack just prior to the elaboration of a package body. The identifier **id** is the package name, and **u**: **Dc** is a declaration continuation that will continue execution (most likely elaboration) at the package body's successor in the environment denoted by **p**.

subprogram return :

$$< \textbf{*SUBPROGRAM-RETURN*}, \textbf{id}, \textbf{p}, \textbf{c} >$$

This descriptor is pushed onto the execution stack after a subprogram (`procedure` or `function`) is entered, but just before the elaboration of the subprogram's local declarations. The identifier **id** is the subprogram name, and **c**: **Sc** is a continuation that will continue execution at the successor of the subprogram call in the environment denoted by **p**.

loop exit :

$$< \textbf{*LOOP-EXIT*, id, p, c} >$$

This descriptor is pushed onto the execution stack when a loop statement (`LOOP`, `WHILE`, or `FOR`) is entered. The identifier **id** is the loop label, and **c**: **Sc** is a continuation that will continue execution at the loop's successor in the environment denoted by **p**.

block exit :

$$< \textbf{*BLOCK-EXIT*, id, p, c} >$$

This descriptor is pushed onto the execution stack just before the elaboration of a `FOR` loop's iteration parameter, which implicitly establishes a block scope. The identifier **id** is the `FOR` loop label, and **c**: **Sc** is a continuation that will continue execution at the `FOR` loop's successor statement in the environment denoted by **p**.

begin marker :

$$< \textbf{*BEGIN*, id, p, c} >$$

This descriptor is pushed onto the execution stack immediately after the local declarations of a subprogram, or the iteration parameter of a `FOR` loop, have been elaborated.

undeclaration :

$$< \textbf{*UNDECLARE*, id}^{+}\textbf{, p, g} >$$

This descriptor, pushed onto the execution stack when a subprogram is called, enables the eventual explicit undeclaration (upon subprogram exit) of the subprogram's formal parameters and other locally declared objects. The identifier list $\textbf{id}^{+}$ names the objects to be undeclared, and **g**: **Sc** $\rightarrow$ **Sc** is a continuation transformer which, after carrying out the explicit undeclaration specified in **g** (thereby popping this ***UNDECLARE*** descriptor from the execution stack), continues execution by means of its continuation argument.

8.3 Special Functions

Certain functions appearing in the semantic specification of Phase 2 translation are not defined denotationally, for either of two reasons: (1) their denotational description is too cumbersome or not well understood, or (2) they are used to construct SDVS-dependent representations of expressions or formulas.

These functions, implemented directly in Common Lisp, are described below.

8.3.1 Operational Semantic Functions

To understand Phase 2 translation, it is important to recognize that in defining the semantics of the VHDL simulation cycle, the VHDL translator involves a significant *operational* component. This is to be distinguished from the semantics of sequential statements within processes, which the translator defines in a primarily *denotational* manner.

We are referring here to our strategy, explained in Section 2, of designing aspects of a *simulator kernel* into the Stage 3 VHDL translator. After application of the state deltas specifying the behavior of one execution cycle for the active processes, the translator is responsible for:

- determining the next VHDL clock time at which a driver becomes active or a process resumes;
- advancing the SDVS state to this new time; and
- generating the state delta that specifies the next sequential statement in the first resuming process for the new execution cycle.

After a given resuming process suspends, its continuation is the textually next resuming process.

It is the internal translator machinery to perform these tasks that is operationally defined — much of it embodied in a portion of the translator that is directly coded in Common Lisp, rather than described by semantic equations. The names of the Common Lisp functions serving this purpose are listed below.

make-vhdl-process-elaborate

make-vhdl-begin-model-execution

make-vhdl-try-resume-next-process

make-vhdl-process-suspend

find-signal-structure

name-driver

init-scalar-signal

init-array-signal-to

init-array-signal-downto

mk-element-waves-aux

get-loop-enum-param-vals

eval-expr

8.3.2 Constructing State Deltas

The construction of state deltas is specified via functions **mk-sd(z)(pre, comod, mod, post)** and **mk-sd-decl(z)(pre, comod, mod, post)**, which take five arguments: the design file name **z** (if **p** is the current path, this is always **hd(p)**) and representations of the precondition, comodification list, modification list, and postcondition of the state delta to be constructed.

These functions are used to represent the construction of state deltas without specifying their exact representation, which is SDVS-dependent and not given here. The pre- and postconditions of a state delta are *lists* of formulas, each of which represents a formula that is the logical *conjunction* of the formulas in this list. If the precondition and comod list arguments of **mk-sd** and **mk-sd-decl** are ϵ, then the precondition and comod list of the constructed state delta are **(TRUE)** and **(ALL)**, respectively. Otherwise, the given arguments are used directly in the state delta. The postcondition may contain a state delta, which is usually represented as a statement continuation applied to an execution stack.

mk-sd and **mk-sd-decl** are almost the same, the only difference being that a state delta created by **mk-sd-decl** is given a special tag that identifies its association with declaration elaboration rather than statement execution.

For technical reasons, the comod list of *every* state delta is **(ALL)** and the mod list of *every* state delta must be *nonempty*. To ensure that a state delta's mod list is never empty, **mk-sd(z)(** ... **)** will *always* prefix **z\pc** to its mod list argument, where **z\pc** is a unique place (represented by a system identifier) in which **z** is the name of the Stage 3 VHDL hardware description being translated. This unique place is the name of a *program counter* whose value implicitly changes when *any* state delta is applied. This program counter place does not make any other kind of appearance in a translated Stage 3 VHDL hardware description.

The notation of state deltas requires that certain symbols sometimes be prefixed to uniquely qualified names: the dot (.) and pound (#) symbols. The functions **dot** and **pound**, applied to uniquely qualified names, accomplish this.

dot(placename) = (**DOT** ,placename)

pound(placename) = (**POUND** ,placename)

Finally, the two functions **fixed-characterized-sds** and **subst-vars** are employed by the Phase 2 semantics of procedure calls to implement the SDVS *offline characterization* mechanism [18, 19], which will be incorporated in Stage 3 VHDL.

8.3.3 Error Reporting

The few kinds of errors that can occur in Phase 2 are reported by the functions **impl-error** and **execution-error**.

The function **impl-error** is used, for example, to report invalid arguments passed to the low-level utility functions **mk-scalar-rel**, **mk-exp1**, and **mk-exp2**, although this should never occur.

The function **execution-error** is used to report execution errors such as an empty execution stack, although again, such errors should never occur if Phase 1 has done its job.

8.4 Phase 2 Semantic Equations

This section constitutes the heart of the present report. It documents the semantic equations and auxiliary semantic functions in terms of which Phase 2 of the Stage 3 VHDL translator — *state delta generation* — is specified denotationally.

8.4.1 Stage 3 VHDL Design Files

```
(DF1) DF [[ DESIGN-FILE id pkg-decl* pkg-body* use-clause* ent-decl arch-body ]] (t)
      = let p0 = %(ε)(id) in
          let id1 = hd(tl(ent-decl)) in
            let p1 = %(p0)(id1) in
              let v = mk-initial-universe(id)
                  and stk = (<*STKBOTTOM* ,id,ε,ε>) in
                (mk-disjoint(id,(dot(id))),
                 mk-cover
                    (dot(id),(catenate(id,"\pc"),VHDLTIME ,VHDLTIME_PREVIOUS )),
                 mk-scalar-decl(VHDLTIME ,(TYPE VHDLTIME) ),
                 mk-scalar-decl(VHDLTIME_PREVIOUS ,(TYPE VHDLTIME) ),
                 mk-rel(vhdltime-type-desc(t))((EQ ,dot(VHDLTIME ),mk-vhdltime(0)(0))),
                 mk-rel
                    (vhdltime-type-desc(t))
                    ((EQ ,dot(VHDLTIME_PREVIOUS ),mk-vhdltime(0)(0))),
                 mk-decl-sd(id)(ε)(ε)(ε)(u1(v)(stk)))
                 where u1 = λv,stk.D [[ pkg-decl* ]] (t)(p0)(u2)(v)(stk)
                 where u2 = λv,stk.D [[ pkg-body* ]] (t)(p0)(u3)(v)(stk)
                 where u3 = λv,stk.D [[ use-clause* ]] (t)(p0)(u4)(v)(stk)
                 where u4 = λv,stk.EN [[ ent-decl ]] (t)(p0)(u5)(v)(stk)
                 where u5 = λv,stk.AR [[ arch-body ]] (t)(p1)(u6)(v)(stk)
                 where u6 = λv,stk.block-exit(v)(stk)

mk-disjoint(id,lst) = cons(ALLDISJOINT ,cons(id,lst))

mk-cover(id,lst) = cons(COVERING ,cons(id,lst))

mk-scalar-decl(placename,place-type) = (DECLARE ,placename,place-type)

vhdltime-type-desc(t) = t((STANDARD) )(VHDLTIME )

mk-rel(d)(op,e1,e2)
= let tg = tag(d) in
    (case tg
       (*BOOL* ,*BIT* ,*INT* ,*REAL* ,*TIME* ,*VHDLTIME* ,*ENUMTYPE* ,*VOID* ,*POLY* )
       → mk-scalar-rel(tg)((op,e1,e2)),
       *SUBTYPE* → mk-scalar-rel(tag(base-type(d)))((op,e1,e2)),
       *INT_TYPE* → mk-scalar-rel(tag(parent-type(d)))((op,e1,e2)),
       *WAVE* → (EQ ,e1,e2),
       *ARRAYTYPE*
       → (is-bitvector-tdesc?(d)
          → (case op
               EQ
               → (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
                  → (EQ ,cons(USCONC ,e1),cons(USCONC ,e2)),
                  is-constant-bitvector?(e2)→ (EQ ,e1,cons(USCONC ,e2)),
                  is-constant-bitvector?(e1)→ (EQ ,cons(USCONC ,e1),e2),
```

```
        (EQ ,e1,e2)),
    NE
    → (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
        → (NEQ ,cons(USCONC ,e1),cons(USCONC ,e2)),
        is-constant-bitvector?(e2)→ (NEQ ,e1,cons(USCONC ,e2)),
        is-constant-bitvector?(e1)→ (NEQ ,cons(USCONC ,e1),e2),
        (NEQ ,e1,e2)),
    LT
    → (EQ ,(BS ,1,1),
        (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
         → (USLSS ,cons(USCONC ,e1),cons(USCONC ,e2)),
         is-constant-bitvector?(e2)→ (USLSS ,e1,cons(USCONC ,e2)),
         is-constant-bitvector?(e1)→ (USLSS ,cons(USCONC ,e1),e2),
         (USLSS ,e1,e2))),
    LE
    → (EQ ,(BS ,1,1),
        (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
         → (USLEQ ,cons(USCONC ,e1),cons(USCONC ,e2)),
         is-constant-bitvector?(e2)→ (USLEQ ,e1,cons(USCONC ,e2)),
         is-constant-bitvector?(e1)→ (USLEQ ,cons(USCONC ,e1),e2),
         (USLEQ ,e1,e2))),
    GT
    → (EQ ,(BS ,1,1),
        (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
         → (USGTR ,cons(USCONC ,e1),cons(USCONC ,e2)),
         is-constant-bitvector?(e2)→ (USGTR ,e1,cons(USCONC ,e2)),
         is-constant-bitvector?(e1)→ (USGTR ,cons(USCONC ,e1),e2),
         (USGTR ,e1,e2))),
    GE
    → (EQ ,(BS ,1,1),
        (is-constant-bitvector?(e1)∧ is-constant-bitvector?(e2)
         → (USGEQ ,cons(USCONC ,e1),cons(USCONC ,e2)),
         is-constant-bitvector?(e2)→ (USGEQ ,e1,cons(USCONC ,e2)),
         is-constant-bitvector?(e1)→ (USGEQ ,cons(USCONC ,e1),e2),
         (USGEQ ,e1,e2))),
    OTHERWISE → impl-error("Shouldn't happen!")),
is-string-tdesc?(d)
→ (case op
    EQ
    → (is-constant-string?(e1)∧ is-constant-string?(e2)
        → (EQ ,cons(ACONC ,e1),cons(ACONC ,e2)),
        is-constant-string?(e2)→ (EQ ,e1,cons(ACONC ,e2)),
        is-constant-string?(e1)→ (EQ ,cons(ACONC ,e1),e2),
        (EQ ,e1,e2)),
    NE
    → (is-constant-string?(e1)∧ is-constant-string?(e2)
        → (NEQ ,cons(ACONC ,e1),cons(ACONC ,e2)),
        is-constant-string?(e2)→ (NEQ ,e1,cons(ACONC ,e2)),
        is-constant-string?(e1)→ (NEQ ,cons(ACONC ,e1),e2),
        (NEQ ,e1,e2)),
    OTHERWISE → impl-error("Shouldn't happen!")),
(case op
  EQ
  → (dotted-expr-p(e2)→ (EQ ,e1,e2), impl-error("Shouldn't happen!")),
  NE
  → (dotted-expr-p(e2)→ (NEQ ,e1,e2),
     impl-error("Shouldn't happen!")),
```

```
            OTHERWISE → impl-error("Shouldn't happen!"))),
        *RECORDTYPE*
        → (dotted-expr-p(e2)→ (EQ ,e1,e2), impl-error("Shouldn't happen!")),
        OTHERWISE → impl-error("Shouldn't happen!"))

is-constant-bitvector?(expr*)
= null(expr*)
   ∨ (consp(expr*)
      ∧ let expr1 = hd(expr*) in
         consp(expr1)∧ hd(expr1)= BS )

is-constant-string?(expr*)
= null(expr*)
   ∨ (consp(expr*)
      ∧ let expr1 = hd(expr*) in
         consp(expr1)∧ hd(expr1)= CHAR )

dotted-expr-p(expr) = consp(expr)∧ hd(expr)= DOT

mk-scalar-rel(type-tag)(relational-op,e1,e2)
= (case type-tag
     *BOOL*
     → (case relational-op
          EQ → mk-bool-eq(type-tag,e1,e2),
          NE → mk-bool-neq(type-tag,e1,e2),
          LT → (AND ,(EQ ,e1,FALSE ),(EQ ,e2,TRUE )),
          LE → (IMPLIES ,e1,e2),
          GT → (AND ,(EQ ,e1,TRUE ),(EQ ,e2,FALSE )),
          GE → (IMPLIES ,e2,e1),
          OTHERWISE
          → impl-error
               ("Unrecognized Stage 3 VHDL BOOLEAN relational operator: ~a",
               relational-op)),
     *BIT*
     → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          LT → (EQ ,(USLSS ,e1,e2),(BS ,1,1)),
          LE → (EQ ,(USLEQ ,e1,e2),(BS ,1,1)),
          GT → (EQ ,(USGTR ,e1,e2),(BS ,1,1)),
          GE → (EQ ,(USGEQ ,e1,e2),(BS ,1,1)),
          OTHERWISE
          → impl-error
               ("Unrecognized Stage 3 VHDL BIT relational operator: ~a",
               relational-op)),
     (*INT* ,*TIME* )
     → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          LT → (LT ,e1,e2),
          LE → (LE ,e1,e2),
          GT → (GT ,e1,e2),
          GE → (GE ,e1,e2),
          OTHERWISE
          → impl-error
               ("Unrecognized Stage 3 VHDL INTEGER relational operator: ~a",
               relational-op)),
```

```
    *VHDLTIME*
    → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          LT → (TIMELT ,e1,e2),
          LE → (TIMELE ,e1,e2),
          GT → (TIMEGT ,e1,e2),
          GE → (TIMEGE ,e1,e2),
          OTHERWISE
          → impl-error
              ("Unrecognized Stage 3 VHDL VHDLTIME relational operator: ~a",
              relational-op)),
    *REAL*
    → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          (RLT ,RLE ,RGT ,RGE ) → (relational-op,e1,e2),
          OTHERWISE
          → impl-error
              ("Unrecognized Stage 3 VHDL REAL relational operator: ~a",
              relational-op)),
    *ENUMTYPE*
    → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          LT → (ELT ,e1,e2),
          LE → (ELE ,e1,e2),
          GT → (EGT ,e1,e2),
          GE → (EGE ,e1,e2),
          PRED → (EPRED ,e1,e2),
          SUCC → (ESUCC ,e1,e2),
          OTHERWISE
          → impl-error
              ("Unrecognized Stage 3 VHDL ENUMERATION relational operator: ~a",
              relational-op)),
    *VOID*
    → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          OTHERWISE
          → impl-error
              ("Unrecognized Stage 3 VHDL VOID relational operator: ~a",
              relational-op)),
    *POLY*
    → (case relational-op
          EQ → (EQ ,e1,e2),
          NE → (NEQ ,e1,e2),
          OTHERWISE
          → impl-error
              ("Unrecognized Stage 3 VHDL POLYMORPHIC relational operator: ~a",
              relational-op)),
    OTHERWISE → impl-error("Unsupported Stage 3 VHDL basic type ~a.",type-tag))

mk-bool-eq(type-tag,e1,e2)
= (type-tag = *BOOL*
    → (simple-term(e1)
        → (simple-term(e2)→ (EQ ,e1,e2), (EQ ,e1,(COND ,e2,TRUE ,FALSE ))),
```

```
        simple-term(e2)→ (EQ ,e2,(COND ,e1,TRUE ,FALSE )),
        (COND ,e1,e2,(NOT ,e2))),
    (EQ ,e1,e2))

mk-bool-neq(type-tag,e1,e2)
= (type-tag = *BOOL*
    → (simple-term(e1)
        → (simple-term(e2)→ (NEQ ,e1,e2), (NEQ ,e1,(COND ,e2,TRUE ,FALSE ))),
        simple-term(e2)→ (NEQ ,e2,(COND ,e1,TRUE ,FALSE )),
        (COND ,e1,e2,(NOT ,e2))),
    (NEQ ,e1,e2))

simple-term(term)
= let operators = (DOT POUND) in
    ¬consp(term)∨ hd(term)∈ operators

mk-vhdltime(global)(delta) = (VHDLTIME ,global,delta)

block-exit(v)(stk)
= let <tg,qname,p,g> = hd(stk) in
    (case tg
        *STKBOTTOM* → model-execution-complete(qname),
        *UNDECLARE* → g(λvv,s.block-exit(vv)(s))(v)(stk),
        (*BLOCK-EXIT* ,*SUBPROGRAM-RETURN* ) → g(v)(stk-pop(stk)),
        (*BEGIN* ,*LOOP-EXIT* ,*PACKAGE-BODY-EXIT* ) → block-exit(v)(stk-pop(stk)),
        OTHERWISE
        → impl-error("Unknown execution stack descriptor with tag: ~a",tg))

model-execution-complete(id)
= (mk-sd(id)(ε)(ε)(ε)(((VHDL_MODEL_EXECUTION_COMPLETE ,id))))
```

A Stage 3 VHDL design file has a name, and consists of some (possibly none) package declarations, package bodies, and USE clauses, followed by an entity declaration and an architecture body.

The semantics of the design file has as its sole semantic argument the TSE **t** constructed by Phase 1. The design file name **id** denotes a special place, whose value **.id** is itself a place that will represent, at any given point during the translation, the current universe of visible places. This name is available to most of the Phase 2 semantic functions as the first edge label in the current path.

Translation of a design file commences by generating some top-level assertions and declarations for the SDVS Simplifier:

- A *disjointness assertion*, required for technical reasons.

  The function **mk-disjoint(place-list)** generates an SDVS assertion stating that the places in **place-list** are mutually disjoint.

- A *covering* assertion that the initial universe of visible places **.id** consists of certain predefined places: the *program counter* place **id\pc** as well as the places **vhdltime** and **vhdltime_previous**.

The function **mk-cover(place, place-list)**[2] generates an SDVS *covering* assertion that **place** covers all the places in **place-list** and that all of the places in **place-list** are mutually disjoint.

- *Declarations* of the places **vhdltime** and **vhdltime_previous**. The function **mk-scalar-decl(placename,place-type)** (make scalar declaration) generates an SDVS declaration of a scalar-value place of the indicated type.

- *Assertions* that the places **vhdltime** and **vhdltime_previous** have as their initial value the time object **vhdltime(0,0)** of the Simplifier VHDL Time domain.

  The function **mk-rel(type-desc)(relation,accessed-place,expression)** (make relation) constructs an SDVS typed relation that asserts that the value of a place at pre- or postcondition time stands in a certain relation to the value of an expression.

Then a state delta that defines the execution of the hardware description is generated. The application of this state delta leads to further usable state deltas, whose generation in the absence of errors is accomplished by continuations. With respect to the TSE **t**, an initial path consisting of the design file's name, an initial universe, and an initial execution stack containing a ***STKBOTTOM*** descriptor to terminate model execution (see Section 8.2), these state deltas symbolically elaborate the design file's package declarations, package bodies, USE clauses, entity declaration, and architecture body.

8.4.2 Entity Declarations

(EN1) $\underline{\mathbf{EN}}$ ⟦ **ENTITY** id decl_1^* decl_2^* opt-id phase1-hook ⟧ (t)(p)(u)(v)(stk)
= **let** $p_1 = \%(p)(id)$ **in**
$\underline{\mathbf{D}}$ ⟦ decl_1^* ⟧ (t)(p_1)(u_1)(v)(stk)
where $u_1 = \lambda v_1,stk_1.\underline{\mathbf{D}}$ ⟦ decl_2^* ⟧ (t)(p_1)(u)(v)(stk)

Phase 2 translation of an entity declaration effects the elaboration, via semantic function **D**, first of its port declarations, and then of any other declarations local to the entity. The interphase abstract syntax tree transformation has arranged for the Phase 2 abstract syntax of port declarations to be identical to that for other objects of class **SIGNAL**.

8.4.3 Architecture Bodies

(AR1) $\underline{\mathbf{AR}}$ ⟦ **ARCHITECTURE** id_1 id_2 decl^* con-stat^* opt-id ⟧ (t)(p)(u)(v)(stk)
= **let** $p_1 = \%(p)(id_1)$ **in**
$\underline{\mathbf{D}}$ ⟦ decl^* ⟧ (t)(p_1)(u_1)(v)(stk)
where
$u_1 = \lambda v_1,stk_1.$
$\underline{\mathbf{CS}}$ ⟦ con-stat^* ⟧ (t)(p_1)(u_2)(v_1)(stk_1)
where
$u_2 = \lambda v_2,stk_2.$

[2]The function **mk-cover** has in some instances been superseded by **mk-cover-already**; it implements an experimental new naming scheme for VHDL variables. The scheme is available only when the SDVS function **new-declarations** is defined to return non-NIL. In SDVS Version 12, this new scheme is not available, so we will not discuss the actions of this function here.

```
cons((VHDL_MODEL_ELABORATION_COMPLETE ,hd(p)),
(mk-sd
    (hd(p))(ε)(ε)(ε)
    ((make-vhdl-begin-model-execution
        (hd(p))(u)(t)(v₂)(stk₂)))))
```

Phase 2 translation of an architecture body first effects the elaboration, via semantic function **D**, of the architecture's local declarations, and then initiates the translation, via semantic function **CS**, of its concurrent statements (which have been uniformly converted to `PROCESS` statements by the interphase abstract syntax tree transformation at the end of Phase 1; see Section 7). The continuation of concurrent statement elaboration returns a Simplifier assertion to the effect that the VHDL model's elaboration is complete, as well as a state delta, constructed by special function `make-vhdl-begin-model-execution`, that initiates symbolic execution of the model.

8.4.4 Declarations

(D0) $\underline{\mathbf{D}}\ [\![\ \varepsilon\ ]\!]\ (t)(p)(u)(v)(stk) = u(v)(stk)$

(D1) $\underline{\mathbf{D}}\ [\![$ decl decl* $]\!]\ (t)(p)(u)(v)(stk)$
$= \underline{\mathbf{D}}\ [\![$ decl $]\!]\ (t)(p)(u_1)(v)(stk)$
where $u_1 = \lambda v_1, stk_1.\underline{\mathbf{D}}\ [\![$ decl* $]\!]\ (t)(p)(u)(v_1)(stk_1)$

(D2) $\underline{\mathbf{D}}\ [\![$ pkg-decl pkg-decl* $]\!]\ (t)(p)(u)(v)(stk)$
$= \underline{\mathbf{D}}\ [\![$ pkg-decl $]\!]\ (t)(p)(u_1)(v)(stk)$
where $u_1 = \lambda v_1, stk_1.\underline{\mathbf{D}}\ [\![$ pkg-decl* $]\!]\ (t)(p)(u)(v_1)(stk_1)$

(D3) $\underline{\mathbf{D}}\ [\![$ pkg-body pkg-body* $]\!]\ (t)(p)(u)(v)(stk)$
$= \underline{\mathbf{D}}\ [\![$ pkg-body $]\!]\ (t)(p)(u_1)(v)(stk)$
where $u_1 = \lambda v_1, stk_1.\underline{\mathbf{D}}\ [\![$ pkg-body* $]\!]\ (t)(p)(u)(v_1)(stk_1)$

(D4) $\underline{\mathbf{D}}\ [\![$ use-clause use-clause* $]\!]\ (t)(p)(u)(v)(stk)$
$= \underline{\mathbf{D}}\ [\![$ use-clause $]\!]\ (t)(p)(u_1)(v)(stk)$
where $u_1 = \lambda v_1, stk_1.\underline{\mathbf{D}}\ [\![$ use-clause* $]\!]\ (t)(p)(u)(v_1)(stk_1)$

The Phase 2 processing of declarations proceeds sequentially, from first to last.

(D5) $\underline{\mathbf{D}}\ [\![$ **DEC** object-class id^+ type-mark opt-expr $]\!]\ (t)(p)(u)(v)(stk)$
$=$ **let** d = lookup-desc(type-mark)(t)(p) **in**

```
(case tag(d)
   (*BOOL* ,*BIT* ,*INT* ,*REAL* ,*TIME* ,*ENUMTYPE* ,*SUBTYPE* ,*INT_TYPE* )
   → gen-scalar-decl
        (decl)(object-class)(id⁺)(d)(opt-expr)(t)(p)(u)(v)(stk),
   *ARRAYTYPE*
   → gen-array-decl
        (decl)(object-class)(id⁺)(d)(direction(d))(real-lb(d))
        (real-ub(d))(elty(d))(opt-expr)(t)(p)(u)(v)(stk),
   *RECORDTYPE*
   → gen-record-decl
        (decl)(object-class)(id⁺)(d)(opt-expr)(t)(p)(u)(v)(stk),
   OTHERWISE → u(v)(stk))
```

```
(D6) D ⟦ SLCDEC object-class id+ slice-name opt-expr ⟧ (t)(p)(u)(v)(stk)
     = let d = lookup(t)(p)(hd(id+)) in
         let anon-array-type-desc = second(type(d)) in
          gen-array-decl
             (decl)(object-class)(id+)(anon-array-type-desc)
             (direction(anon-array-type-desc))(lb(anon-array-type-desc))
             (ub(anon-array-type-desc))(elty(anon-array-type-desc))(opt-expr)(t)(p)
             (u)(v)(stk)


lookup-desc(id*)(t)(p)
= (null(id*)→ void-type-desc(t),
   let q = access(rest(id*))(t)(p) in
    lookup-desc-on-path(t)(q)(last(id*)))

lookup-desc-on-path(t)(p)(id)
= let d = t(p)(id) in
   (d = *UNBOUND* → lookup-desc-on-path(t)(rest(p))(id), d)

access(id*)(t)(p)
= (null(id*)→ p,
   let d = lookup(t)(p)(hd(id*)) in
    access(tl(id*))(t)(%(path(d))(idf(d))))

gen-scalar-decl(decl)(object-class)(id+)(d)(expr)(t)(p)(u)(v)(stk)
= (null(expr)
   → gen-scalar-decl-id+(decl)(object-class)(id+)(d)(expr)(t)(p)(u)(v)(stk),
   gen-scalar-decl-id*(decl)(object-class)(id+)(d)(expr)(t)(p)(u)(v)(stk))

gen-scalar-decl-id+(decl)(object-class)(id+)(d)(expr)(t)(p)(u)(v)(stk)
= (object-class = SIG
   → gen-scalar-signal-decl-id+(decl)(id+)(d)(expr)(t)(p)(u)(v)(stk),
   gen-scalar-nonsignal-decl-id+(decl)(id+)(d)(expr)(t)(p)(u)(v)(stk))

gen-scalar-decl-id*(decl)(object-class)(id*)(d)(expr)(t)(p)(u)(v)(stk)
= (null(id*)→ u(v,stk),
   let id+ = (hd(id*)) in
    gen-scalar-decl-id+(decl)(object-class)(id+)(d)(expr)(t)(p)(u1)(v)(stk)
     where
     u1 = λv1,stk1.
            gen-scalar-decl-id*
               (decl)(object-class)(tl(id*))(d)(expr)(t)(p)(u)(v1)(stk1))


gen-scalar-nonsignal-decl-id+(decl)(id+)(d)(expr)(t)(p)(u)(v)(stk)
= R ⟦ expr ⟧ (t)(p)(k)(v)(stk)
   where
   k = λ(e,f),v1,stk1.
        let z = hd(p)
            and suqn+ = get-qids(id+)(t)(p) in
         let v2 = push-universe(v1)(z)(suqn+) in
          let duqn+ = get-qualified-ids(suqn+)(v2) in
           (mk-decl-sd
              (z)(f)(ε)((z))
              (nconc
                 (mk-qual-id-coverings(suqn+)(duqn+)(z)(v)(t),
                 mk-scalar-nonsignal-dec-post
                    (decl)((duqn+,e,d))(t)(p)(u)(v2)(stk))))
```

```
get-qids(id*)(t)(p)
= (null(id*)→ ε, cons(qid(t(p)(hd(id*))),get-qids(tl(id*))(t)(p)))

get-qualified-ids(suqn*)(v)
= (null(suqn*)→ ε,
   cons(qualified-id(hd(suqn*))(v),get-qualified-ids(tl(suqn*))(v)))

qualified-id(suqn)(v)
= let vars = universe-vars(v) in
    let suqn-triple = assoc(suqn,vars) in
     (suqn-triple
      → let n = hd(third(suqn-triple)) in
          name-qualified-id(suqn)(n),
      name-qualified-id(suqn)(1))

name-qualified-id(suqn)(n)
= (new-declarations()→ (PLACELEMENT ,suqn,n),
   (n = 1 → suqn, catenate(suqn,"!",n)))

already-qualified-id(suqn)(v) = ¬null(assoc(suqn,universe-vars(v)))

qualified-id-decls(suqn*)
= (null(suqn*)→ ε,
   let suqn = hd(suqn*) in
    cons((DECLARE ,suqn,(TYPE ,PLACEARRAY )),qualified-id-decls(tl(suqn*))))

mk-qual-id-coverings(suqn+)(duqn+)(z)(v)(t)
= (new-declarations()
   → (already-qualified-id(hd(suqn+))(v)
      → (mk-rel(univint-type-desc(t))((EQ ,pound(z),dot(z)))),
      nconc
         ((mk-disjoint(z,cons(dot(z),suqn+)),
           mk-cover(pound(z),cons(dot(z),suqn+))),qualified-id-decls(suqn+))),
   (mk-disjoint(z,cons(dot(z),duqn+)),mk-cover(pound(z),cons(dot(z),duqn+))))

mk-scalar-nonsignal-dec-post(decl)(duqn*,e,d)(t)(p)(u)(v)(stk)
= let type-spec = mk-type-spec(d)(t)(p) in
    (null(e)
     → nconc
         (mk-scalar-nonsignal-dec-post-declare(duqn*)(type-spec),
         u(v)(stk)),
     nconc
        (mk-scalar-nonsignal-dec-post-declare(duqn*)(type-spec),
        u1(v)(stk))
      where
      u1 = λv1,stk1.
            (mk-decl-sd
               (hd(p))(ε)(ε)(duqn*)
               (nconc
                  (mk-scalar-nonsignal-dec-post-init(duqn*)(e)(d),
                  u(v1)(stk1)))))

mk-type-spec(d)(t)(p)
= (case tag(d)
     *BOOL* → (TYPE BOOLEAN) ,
     *BIT* → (TYPE BIT) ,
     (*INT* ,*INT_TYPE* ,*TIME* ) → (TYPE INTEGER) ,
```

```
      *REAL* → (TYPE FLOAT) ,
      *VHDLTIME* → (TYPE VHDLTIME) ,
      *ENUMTYPE*
      → (idf(d)= CHARACTER → (TYPE CHARACTER) ,
          cons(TYPE ,cons(ENUMERATION ,literals(d)))),
      *SUBTYPE* → mk-type-spec(base-type(d))(t)(p),
      *VOID* → (TYPE VOID) ,
      *POLY* → (TYPE POLYMORPHIC) ,
      *RECORDTYPE* → cons(TYPE ,cons(RECORD ,record-to-type(components(d))(t)(p))),
      *ARRAYTYPE*
      → let expr1 = lb(d) in
          R ⟦ expr1 ⟧ (t)(p)(k1)(ε)(ε)
          where
          k1 = λ(e1,f1),v1,stk1.
                let expr2 = ub(d) in
                 R ⟦ expr2 ⟧ (t)(p)(k2)(v1)(stk1)
                 where
                 k2 = λ(e2,f2),v2,stk2.
                       cons(TYPE ,
                       (ARRAY ,e1,e2,mk-type-spec(elty(d))(t)(p))),
      *WAVE* → (TYPE ,WAVEFORM ,mk-type-spec(hd(type(d)))(t)(p)),
      OTHERWISE → impl-error("Unrecognized Stage 3 VHDL type: ~a",tag(d)))

record-to-type(record-components)(t)(p)
= (null(record-components)→ ε,
    let (id,d) = hd(record-components) in
     cons((id,mk-type-spec(d)(t)(p)),
     record-to-type(tl(record-components))(t)(p)))

mk-scalar-nonsignal-dec-post-declare(duqn*)(type-spec)
= (null(duqn*)→ ε,
    let duqn = hd(duqn*) in
     cons(mk-scalar-decl(duqn,type-spec),
     mk-scalar-nonsignal-dec-post-declare(tl(duqn*))(type-spec)))

mk-scalar-decl(placename,place-type) = (DECLARE ,placename,place-type)

mk-scalar-nonsignal-dec-post-init(duqn*)(e)(d)
= (null(duqn*)→ ε,
    let duqn = hd(duqn*) in
     nconc
       (assign(d)((duqn,e)),mk-scalar-nonsignal-dec-post-init(tl(duqn*))(e)(d)))

assign(d)(target,value)
= (case tag(d)
     (*BOOL* ,*BIT* ,*INT* ,*REAL* ,*TIME* ,*VHDLTIME* ,*ENUMTYPE* ,*WAVE* ,
      *VOID* ,*POLY* )
     → (mk-rel(d)((EQ ,pound(target),value))),
     *SUBTYPE* → assign(base-type(d))((target,value)),
     *INT_TYPE* → assign(parent-type(d))((target,value)),
     *ARRAYTYPE*
     → (is-bitvector-tdesc?(d)
         → (is-constant-bitvector?(value)
             → (case direction(d)
                  TO
                  → assign-array-to
                       (target)(value)(elty(d))((ORIGIN ,target))(0),
```

```
                DOWNTO
                → assign-array-downto
                      (target)(value)(elty(d))
                      (mk-exp2
                          (SUB ,
                          mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),1))(0),
                OTHERWISE → impl-error("Illegal direction: ~a",direction
                                                                    (d))),
            (mk-rel(d)((EQ ,pound(target),value)))),
        is-string-tdesc?(d)
        → (is-constant-string?(value)
            → (case direction(d)
                TO
                → assign-array-to
                      (target)(value)(elty(d))((ORIGIN ,target))(0),
                DOWNTO
                → assign-array-downto
                      (target)(value)(elty(d))
                      (mk-exp2
                          (SUB ,
                          mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),1))(0),
                OTHERWISE → impl-error("Illegal direction: ~a",direction
                                                                    (d))),
            (mk-rel(d)((EQ ,pound(target),value)))),
          (dotted-expr-p(value)→ (mk-rel(d)((EQ ,pound(target),value))),
           (case direction(d)
            TO → assign-array-to(target)(value)(elty(d))((ORIGIN ,target))(0),
            DOWNTO
            → assign-array-downto
                  (target)(value)(elty(d))
                  (mk-exp2
                      (SUB ,mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),
                      1))(0),
            OTHERWISE → impl-error("Illegal direction: ~a",direction(d))))),
      *RECORDTYPE*
      → (dotted-expr-p(value)→ assign-record(d)((target,value)),
          assign-record-fields(components(d))((target,value))),
      OTHERWISE → impl-error("Unrecognized Stage 3 VHDL type tag: ~a",tag(d)))

is-constant-bitvector?(expr*)
= null(expr*)
   ∨ (consp(expr*)
      ∧ let expr1 = hd(expr*) in
          consp(expr1)∧ hd(expr1)= BS )

is-constant-string?(expr*)
= null(expr*)
   ∨ (consp(expr*)
      ∧ let expr1 = hd(expr*) in
          consp(expr1)∧ hd(expr1)= CHAR )

dotted-expr-p(expr) = consp(expr)∧ hd(expr)= DOT

assign-array-to(target)(aggregate)(element-type-desc)(start-index)(m)
= (null(aggregate)→ ε,
    nconc
      (assign
```

```
        (element-type-desc)
        (((ELEMENT ,target,mk-exp2(ADD ,start-index,m)),hd(aggregate))),
      assign-array-to
        (target)(tl(aggregate))(element-type-desc)(start-index)(m+1)))

assign-array-downto(target)(aggregate)(element-type-desc)(start-index)(m)
= (null(aggregate)→ ε,
   nconc
     (assign
        (element-type-desc)
        (((ELEMENT ,target,mk-exp2(SUB ,start-index,m)),hd(aggregate))),
      assign-array-downto
        (target)(tl(aggregate))(element-type-desc)(start-index)(m+1)))

mk-exp2(binary-op,e1,e2)
= (case binary-op
     AND → (AND ,e1,e2),
     NAND → (NAND ,e1,e2),
     OR → (OR ,e1,e2),
     NOR → (NOR ,e1,e2),
     XOR → (XOR ,e1,e2),
     BAND → (USAND ,e1,e2),
     BNAND → (USNAND ,e1,e2),
     BOR → (USOR ,e1,e2),
     BNOR → (USNOR ,e1,e2),
     BXOR → (USXOR ,e1,e2),
     ADD → (PLUS ,e1,e2),
     SUB → (MINUS ,e1,e2),
     MUL → (MULT ,e1,e2),
     DIV → (DIV ,e1,e2),
     MOD → (MOD ,e1,e2),
     REM → (REM ,e1,e2),
     EXP → (EXPT ,e1,e2),
     (RPLUS ,RMINUS ,RTIMES ,RDIV ,REXPT ) → (binary-op,e1,e2),
     CONCAT → (ACONC ,e1,e2),
     OTHERWISE
     → impl-error("Unrecognized Stage 3 VHDL binary operator: ~a",binary-op))

assign-record(d)(target-record,dotted-source-record)
= cons(mk-rel(d)((EQ ,pound(target-record),dotted-source-record)),
   assign-record-aux
     (components(d))((target-record,second(dotted-source-record))))

assign-record-aux(comp*)(target-record,source-record-name)
= (null(comp*)→ ε,
   let (id,d) = hd(comp*) in
     nconc
       (assign
          (d)
          ((mk-recelt(target-record,id),dot(mk-recelt(source-record-name,id)))),
        assign-record-aux(tl(comp*))((target-record,source-record-name))))

assign-record-fields(comp*)(target-record,source-fields)
= (null(comp*)→ ε,
   let (id,d) = hd(comp*) in
     nconc
       (assign(d)((mk-recelt(target-record,id),second(assoc(id,source-fields)))),
        assign-record-fields(tl(comp*))((target-record,source-fields))))
```

```
mk-recelt(e)(id) = (RECORD ,e,id)


gen-scalar-signal-decl-id+(decl)(id+)(d)(expr)(t)(p)(u)(v)(stk)
= R [[ expr ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v1,stk1.
          let z = hd(p)
              and signal-suqn+ = get-qids(id+)(t)(p) in
           let driver-suqn+ = name-drivers(signal-suqn+) in
            let suqn+ = append(signal-suqn+,driver-suqn+) in
             let v2 = push-universe(v1)(z)(suqn+) in
              let signal-duqn+ = get-qualified-ids(signal-suqn+)(v2)
                  and driver-duqn+ = get-qualified-ids(driver-suqn+)(v2) in
               let duqn+ = append(signal-duqn+,driver-duqn+) in
                (mk-decl-sd
                   (z)(f)(ε)((z))
                   (nconc
                      (mk-qual-id-coverings(suqn+)(duqn+)(z)(v)(t),
                      mk-scalar-signal-dec-post
                         (decl)((duqn+,signal-duqn+,driver-duqn+,e,d))(t)(p)(u)
                         (v2)(stk))))

name-drivers(signal-names)
= (null(signal-names)→ ε,
   cons(name-driver(hd(signal-names)),name-drivers(tl(signal-names))))

mk-scalar-signal-dec-post(decl)(duqn*,signal-duqn*,driver-duqn*,e,d)(t)(p)(u)(v)(stk)
= let sigtype-spec = mk-sigtype-spec(d)(t)(p)
      and waveform-type-spec = (TYPE ,WAVEFORM ,mk-type-spec(d)(t)(p)) in
    nconc
      (mk-scalar-signal-dec-post-declare
         (signal-duqn*)(driver-duqn*)(sigtype-spec)(waveform-type-spec),
      u1(v)(stk))
     where
     u1 = λv1,stk1.
           (mk-decl-sd
              (hd(p))(ε)(ε)(duqn*)
              (nconc
                 (mk-scalar-signal-dec-post-init
                    (signal-duqn*)(driver-duqn*)(e)(d)(waveform-type-desc(d)),
                 u(v1)(stk1))))

mk-scalar-signal-dec-post-declare(signal-duqn*)(driver-duqn*)(sigtype-spec)(waveform-type-spec)
= (null(signal-duqn*)→ ε,
   let signal-duqn = hd(signal-duqn*)
       and driver-duqn = hd(driver-duqn*) in
     nconc
       (mk-scalar-signal-decl
          ((signal-duqn,driver-duqn))((sigtype-spec,waveform-type-spec)),
       mk-scalar-signal-dec-post-declare
          (tl(signal-duqn*))(tl(driver-duqn*))(sigtype-spec)(waveform-type-spec)))

mk-scalar-signal-decl(signal-name,driver-name)(sigtype-spec,waveform-type-spec)
= (mk-scalar-decl(signal-name,sigtype-spec),
   mk-scalar-decl(driver-name,waveform-type-spec))
```

```
mk-scalar-signal-fn-decl(signal-name,driver-name)
= (DECLARE ,signal-name,(TYPE ,FN ,(VAL ,dot(driver-name),dot(VHDLTIME ))))

waveform-type-desc(type-desc) = <WAVEFORM ,ε,*WAVE* ,(STANDARD) ,tt,type-desc>

mk-scalar-signal-dec-post-init(signal-duqn*)(driver-duqn*)(e)(type-desc)(waveform-type-desc)
= (null(signal-duqn*)→ ε,
    let signal-duqn = hd(signal-duqn*)
        and driver-duqn = hd(driver-duqn*) in
     let initial-signal-val = (null(e)→ eval-expr(dot(signal-duqn)), e) in
      let initial-waveform = init-scalar-signal
                                (signal-duqn)(driver-duqn)(type-desc)
                                (initial-signal-val) in
        nconc
          (assign(waveform-type-desc)((driver-duqn,initial-waveform)),
          mk-scalar-signal-dec-post-init
            (tl(signal-duqn*))(tl(driver-duqn*))(e)(type-desc)(waveform-type-desc)))


gen-array-decl(decl)
              (object-class)(id+)(type-desc)(direction)(lower-bound)(upper-bound)(element-type-desc)(expr)
              (t)(p)(u)(v)(stk)
= (null(expr)
    → gen-array-decl-id+
        (decl)(object-class)(id+)(type-desc)(direction)(lower-bound)(upper-bound)
        (element-type-desc)(expr)(t)(p)(u)(v)(stk),
    gen-array-decl-id*
      (decl)(object-class)(id+)(type-desc)(direction)(lower-bound)(upper-bound)
      (element-type-desc)(expr)(t)(p)(u)(v)(stk))

real-lb(d)
= let bound = lb(d) in
    (is-num-lit?(bound)→ bound,
     (REF ,((SREF ,path(d),mk-tick-low(idf(d))))))

real-ub(d)
= (path(d)= (STANDARD) ∧ idf(d)∈ (STRING BIT_VECTOR) → ε,
    let bound = ub(d) in
     (is-num-lit?(bound)→ bound,
      (REF ,((SREF ,path(d),mk-tick-high(idf(d)))))))

mk-tick-low(id) = catenate(id,"'LOW")

mk-tick-high(id) = catenate(id,"'HIGH")

gen-array-decl-id+(decl)
                  (object-class)(id+)(type-desc)(direction)(lower-bound)(upper-bound)(element-type-desc)(expr)
                  (t)(p)(u)(v)(stk)
= (object-class = SIG
    → gen-array-signal-decl-id+
        (decl)(id+)(type-desc)(direction)(lower-bound)(upper-bound)
        (element-type-desc)(expr)(t)(p)(u)(v)(stk),
    gen-array-nonsignal-decl-id+
      (decl)(id+)(direction)(lower-bound)(upper-bound)(element-type-desc)(expr)
      (t)(p)(u)(v)(stk))
```

```
gen-array-decl-id*(decl)
                  (object-class)(id*)(type-desc)(direction)(lower-bound)(upper-bound)(element-type-desc)(expr)
                  (t)(p)(u)(v)(stk)
= (null(id*)→ u(v,stk),
   let id+ = (hd(id*)) in
    gen-array-decl-id+
      (decl)(object-class)(id+)(type-desc)(direction)(lower-bound)(upper-bound)
      (element-type-desc)(expr)(t)(p)(u1)(v)(stk)
     where
     u1 = λv1,stk1.
          gen-array-decl-id*
            (decl)(object-class)(tl(id*))(type-desc)(direction)(lower-bound)
            (upper-bound)(element-type-desc)(expr)(t)(p)(u)(v1)(stk1))


gen-array-nonsignal-decl-id+(decl)
                            (id+)(direction)(expr1)(expr2)(element-type-desc)(expr)
                            (t)(p)(u)(v)(stk)
= R [[ expr ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v1,stk1.
         R [[ expr1 ]] (t)(p)(k1)(v1)(stk1)
          where
          k1 = λ(e1,f1),v2,stk2.
               R [[ expr2 ]] (t)(p)(k2)(v2)(stk2)
                where
                k2 = λ(e2,f2),v3,stk3.
                     let z = hd(p)
                         and len = length-expr(expr)
                         and suqn+ = get-qids(id+)(t)(p) in
                      let v4 = push-universe(v3)(z)(suqn+) in
                       let duqn+ = get-qualified-ids(suqn+)(v4) in
                        let g1 = (e1 ∧ e2
                                  → mk-rel
                                       (univint-type-desc(t))
                                       ((LE ,e1,e2)),
                                  TRUE )
                            and g2 = (e1 ∧ e2
                                      → mk-rel
                                           (univint-type-desc(t))
                                           ((GE ,
                                             mk-exp2
                                               (ADD ,mk-exp2(SUB ,e2,e1),
                                               1),len)),
                                      TRUE ) in
                         (mk-decl-sd
                             (z)
                             (nconc
                                 (f1,f2,(g1),
                                 (len = 0 → f, nconc((g2),f))))(ε)((z))
                             (nconc
                                 (mk-qual-id-coverings
                                     (suqn+)(duqn+)(z)(v)(t),
                                 mk-array-nonsignal-dec-post
                                    (decl)
                                    ((duqn+,e,direction,e1,e2,element-type-desc))
                                    (t)(p)(u)(v4)(stk3))))
```

```
length-expr(expr)
= (null(expr)→ 0,
   hd(expr)∈ (BITSTR STR PAGGR) → length(second(expr)),
   1)

mk-array-nonsignal-dec-post(decl)
                            (duqn*,e,direction,lower-bound,upper-bound,element-type-desc)
                            (t)(p)(u)(v)(stk)
= let element-type-spec = mk-type-spec(element-type-desc)(t)(p) in
    (null(e)
     → nconc
          (mk-array-nonsignal-dec-post-declare
              (duqn*)(direction)(lower-bound)(upper-bound)(element-type-spec),
          u(v)(stk)),
     nconc
       (mk-array-nonsignal-dec-post-declare
           (duqn*)(direction)(lower-bound)(upper-bound)(element-type-spec),
       u1(v)(stk))
      where
      u1 = λv1,stk1.
             (mk-decl-sd
                 (hd(p))(ε)(ε)(duqn*)
                 (nconc
                     ((direction = TO
                       → mk-array-nonsignal-dec-post-init-to
                             (duqn*)(e)(element-type-desc)(lower-bound),
                       mk-array-nonsignal-dec-post-init-downto
                          (duqn*)(e)(element-type-desc)(upper-bound)),
                      u(v1)(stk1)))))

mk-array-nonsignal-dec-post-declare(duqn*)(direction)(lower-bound)(upper-bound)(element-type-spec)
= (null(duqn*)→ ε,
   let duqn = hd(duqn*) in
    nconc
      (mk-vhdl-array-decl
          (duqn)(direction)(lower-bound)
          ((null(upper-bound)
            → (lower-bound = 1 → (RANGE ,duqn),
                mk-exp2(SUB ,mk-exp2(ADD ,(RANGE ,duqn),lower-bound),1)),
           upper-bound))(element-type-spec),
      mk-array-nonsignal-dec-post-declare
         (tl(duqn*))(direction)(lower-bound)(upper-bound)(element-type-spec)))

mk-vhdl-array-decl(id)(direction)(lower-bound)(upper-bound)(element-type-spec)
= (case second(element-type-spec)
     BIT
     → (mk-array-decl(id)(lower-bound)(upper-bound)(element-type-spec),
        mk-bitvec-fn-decl(id)(direction)(lower-bound)(upper-bound)),
     CHARACTER
     → (mk-array-decl(id)(lower-bound)(upper-bound)(element-type-spec),
        mk-string-fn-decl(id)(direction)(lower-bound)(upper-bound)),
     OTHERWISE
     → (mk-array-decl(id)(lower-bound)(upper-bound)(element-type-spec)))

mk-array-decl(id)(lower-bound)(upper-bound)(element-type-spec)
= (DECLARE ,id,(TYPE ,ARRAY ,lower-bound,upper-bound,element-type-spec))
```

```
mk-bitvec-fn-decl(bitvec-name)(direction)(lower-bound)(upper-bound)
= let  bitvec-elt-names = (direction = TO
                          → mk-slice-elt-names-to
                              (bitvec-name)(lower-bound)(upper-bound),
                          mk-slice-elt-names-downto
                            (bitvec-name)(lower-bound)(upper-bound))  in
    (DECLARE ,bitvec-name,(TYPE ,FN ,concatenate-bits(bitvec-elt-names)))

mk-string-fn-decl(string-name)(direction)(lower-bound)(upper-bound)
= let  string-elt-names = (direction = TO
                          → mk-slice-elt-names-to
                              (string-name)(lower-bound)(upper-bound),
                          mk-slice-elt-names-downto
                            (string-name)(lower-bound)(upper-bound))  in
    (DECLARE ,string-name,(TYPE ,FN ,concatenate-characters(string-elt-names)))

mk-slice-elt-names-to(slice-name)(lower-bound)(upper-bound)
= (lower-bound > upper-bound → ε,
    cons(mk-array-elt(slice-name)(lower-bound),
    mk-slice-elt-names-to(slice-name)(lower-bound+1)(upper-bound)))

mk-slice-elt-names-downto(slice-name)(lower-bound)(upper-bound)
= (upper-bound < lower-bound → ε,
    cons(mk-array-elt(slice-name)(upper-bound),
    mk-slice-elt-names-downto(slice-name)(lower-bound)(upper-bound−1)))

mk-array-elt(id)(e) = (ELEMENT ,id,e)

concatenate-bits(bit-names) = cons(USCONC ,mk-dotted-names(bit-names))

concatenate-characters(char-names) = cons(ACONC ,mk-dotted-names(char-names))

mk-dotted-names(names)
= (null(names)→ ε, cons(dot(hd(names)),mk-dotted-names(tl(names))))

mk-array-nonsignal-dec-post-init-to(duqn*)(e)(element-type-desc)(lower-bound)
= (null(duqn*)→ ε,
    nconc
      (assign-array-to(hd(duqn*))(e)(element-type-desc)(lower-bound)(0),
      mk-array-nonsignal-dec-post-init-to
        (tl(duqn*))(e)(element-type-desc)(lower-bound)))

mk-array-nonsignal-dec-post-init-downto(duqn*)(e)(element-type-desc)(upper-bound)
= (null(duqn*)→ ε,
    nconc
      (assign-array-downto(hd(duqn*))(e)(element-type-desc)(upper-bound)(0),
      mk-array-nonsignal-dec-post-init-downto
        (tl(duqn*))(e)(element-type-desc)(upper-bound)))


gen-array-signal-decl-id+(decl)
                         (id+)(type-desc)(direction)(expr1)(expr2)(element-type-desc)(expr)
                         (t)(p)(u)(v)(stk)
= R ⟦ expr ⟧ (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v1,stk1.
          R ⟦ expr1 ⟧ (t)(p)(k1)(v1)(stk1)
```

```
            where
            k1 = λ(e1,f1),v2,stk2.
                  R [[ expr2 ]] (t)(p)(k2)(v2)(stk2)
                   where
                   k2 = λ(e2,f2),v3,stk3.
                         let z = hd(p)
                             and len = length-expr(expr)
                             and signal-suqn+ = get-qids(id+)(t)(p) in
                          let driver-suqn+ = name-drivers(signal-suqn+) in
                           let suqn+ = append(signal-suqn+,driver-suqn+) in
                            let v4 = push-universe(v3)(z)(suqn+) in
                             let signal-duqn+ = get-qualified-ids
                                                   (signal-suqn+)(v4)
                                 and driver-duqn+ = get-qualified-ids
                                                       (driver-suqn+)(v4) in
                              let duqn+ = append
                                             (signal-duqn+,driver-duqn+) in
                               let g1 = (e1 ∧ e2
                                         → mk-rel
                                              (univint-type-desc(t))
                                              ((LE ,e1,e2)),
                                           TRUE )
                                   and g2 = (e1 ∧ e2
                                             → mk-rel
                                                  (univint-type-desc(t))
                                                  ((GE ,
                                                    mk-exp2
                                                       (ADD ,
                                                       mk-exp2(SUB ,e2,e1),1),len)),
                                                TRUE ) in
                                (mk-decl-sd
                                   (z)
                                   (nconc
                                      (f1,f2,(g1),
                                      (len = 0 → f, nconc(f,(g2)))))(ε)((z))
                                   (nconc
                                      (mk-qual-id-coverings
                                         (suqn+)(duqn+)(z)(v)(t),
                                      mk-array-signal-dec-post
                                         (decl)
                                         ((duqn+,signal-duqn+,driver-duqn+,e,type-desc,direction,
                                           e1,e2,element-type-desc))(t)(p)(u)
                                         (v4)(stk3))))

mk-array-signal-dec-post(decl)
                        (duqn*,signal-duqn*,driver-duqn*,e,type-desc,
                         direction,lower-bound,upper-bound,element-type-desc)
                        (t)(p)(u)(v)(stk)
= let element-sigtype-spec = mk-sigtype-spec(element-type-desc)(t)(p)
      and element-waveform-type-spec = mk-waveform-type-spec
                                          (mk-type-spec(element-type-desc)(t)(p)) in
   nconc
     (mk-array-signal-dec-post-declare
        (signal-duqn*)(driver-duqn*)(direction)(lower-bound)(upper-bound)
        (element-sigtype-spec)(element-waveform-type-spec)(tt)(t)(p)(v)(stk),
     u1(v)(stk))
    where
```

```
    u1 = λv1,stk1.
           (mk-decl-sd
              (hd(p))(ε)(ε)(duqn*)
              (nconc
                 (mk-array-signal-dec-post-init
                    (signal-duqn*)(driver-duqn*)(e)(type-desc)(direction)
                    (lower-bound)(upper-bound)(element-type-desc)
                    (waveform-type-desc(element-type-desc))(t)(p)(v)(stk),
                 u(v1)(stk1))))

mk-waveform-type-spec(type-spec)
= (case second(type-spec)
     ARRAY → append(rest(type-spec),(mk-waveform-type-spec(last(type-spec)))),
     OTHERWISE → (TYPE ,WAVEFORM ,type-spec))

mk-array-signal-dec-post-declare(signal-duqn*)(driver-duqn*)(direction)(lower-bound)(upper-bound)
                                (element-sigtype-spec)(element-waveform-type-spec)(fn-decls?)
                                (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
   let signal-duqn = hd(signal-duqn*)
       and driver-duqn = hd(driver-duqn*) in
     nconc
       (mk-array-signal-decl
          (signal-duqn)(driver-duqn)(direction)(lower-bound)(upper-bound)
          (element-sigtype-spec)(element-waveform-type-spec)(fn-decls?)(t)(p)(v)
          (stk),
       mk-array-signal-dec-post-declare
          (tl(signal-duqn*))(tl(driver-duqn*))(direction)(lower-bound)
          (upper-bound)(element-sigtype-spec)(element-waveform-type-spec)
          (fn-decls?)(t)(p)(v)(stk)))

mk-array-signal-decl(signal-name)(driver-name)(direction)(lower-bound)(upper-bound)
                    (element-sigtype-spec)(element-waveform-type-spec)(fn-decls?)
                    (t)(p)(v)(stk)
= nconc
     (mk-vhdl-sigarray-decl
        (signal-name)(direction)(lower-bound)
        ((null(upper-bound)
          → (lower-bound = 1 → (RANGE ,signal-name),
             mk-exp2(SUB ,mk-exp2(ADD ,(RANGE ,signal-name),lower-bound),1)),
          upper-bound))(element-sigtype-spec)(fn-decls?),
     (mk-array-decl
        (driver-name)(lower-bound)
        ((null(upper-bound)
          → (lower-bound = 1 → (RANGE ,driver-name),
             mk-exp2(SUB ,mk-exp2(ADD ,(RANGE ,driver-name),lower-bound),1)),
          upper-bound))(element-waveform-type-spec)))

mk-array-signal-elt-fn-decls(signal-duqn)(driver-duqn)(element-type-desc)(lower-bound)(upper-bound)
                            (t)(p)(v)(stk)
= (is-array-tdesc?(element-type-desc)
   → let signal-elts = mk-slice-elt-names-to
                            (signal-duqn)(lower-bound)(upper-bound)
       and driver-elts = mk-slice-elt-names-to
                            (driver-duqn)(lower-bound)(upper-bound) in
     let expr1 = real-lb(element-type-desc) in
      R ⟦ expr1 ⟧ (t)(p)(k1)(v)(stk)
```

```
        where
        k1 = λ(e1,f1),v1,stk1.
               let expr2 = real-ub(element-type-desc) in
                R ⟦ expr2 ⟧ (t)(p)(k2)(v1)(stk1)
                where
                k2 = λ(e2,f2),v2,stk2.
                       mk-array-signal-elt-fn-decls-aux
                          (signal-elts)(driver-elts)(elty(element-type-desc))
                          (e1)(e2)(t)(p)(v2)(stk2),
   let scalar-signal-elts = mk-slice-elt-names-to
                               (signal-duqn)(lower-bound)(upper-bound)
       and scalar-driver-elts = mk-slice-elt-names-to
                                   (driver-duqn)(lower-bound)(upper-bound) in
    mk-scalar-signal-fn-decls(scalar-signal-elts,scalar-driver-elts))

mk-array-signal-elt-fn-decls-aux(signal-duqn*)(driver-duqn*)
                                (element-type-desc)(lower-bound)(upper-bound)
                                (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
   let signal-duqn = hd(signal-duqn*)
       and driver-duqn = hd(driver-duqn*) in
    nconc
       (mk-array-signal-elt-fn-decls
          (signal-duqn)(driver-duqn)(element-type-desc)(lower-bound)(upper-bound)
          (t)(p)(v)(stk),
       mk-array-signal-elt-fn-decls-aux
          (tl(signal-duqn*))(tl(driver-duqn*))(element-type-desc)(lower-bound)
          (upper-bound)(t)(p)(v)(stk)))

mk-scalar-signal-fn-decls(signal-names,driver-names)
= (null(signal-names)→ ε,
   cons(mk-scalar-signal-fn-decl(hd(signal-names),hd(driver-names)),
   mk-scalar-signal-fn-decls(tl(signal-names),tl(driver-names))))

mk-array-signal-dec-post-init(signal-duqn*)(driver-duqn*)(e)
                             (type-desc)(direction)(lower-bound)(upper-bound)
                             (element-type-desc)(element-waveform-type-desc)
                             (t)(p)(v)(stk)
= (direction = TO
   → mk-array-signal-dec-post-init-to
        (signal-duqn*)(driver-duqn*)(e)(type-desc)(lower-bound)(upper-bound)
        (element-type-desc)(element-waveform-type-desc)(t)(p)(v)(stk),
   mk-array-signal-dec-post-init-downto
      (signal-duqn*)(driver-duqn*)(e)(type-desc)(lower-bound)(upper-bound)
      (element-type-desc)(element-waveform-type-desc)(t)(p)(v)(stk))

mk-array-signal-dec-post-init-to(signal-duqn*)(driver-duqn*)(e)
                                (type-desc)(lower-bound)(upper-bound)
                                (element-type-desc)(element-waveform-type-desc)
                                (t)(p)(v)(stk)
= (is-array-tdesc?(element-type-desc)
   → let expr1 = real-lb(element-type-desc) in
       R ⟦ expr1 ⟧ (t)(p)(k1)(v)(stk)
       where
       k1 = λ(e1,f1),v1,stk1.
              let expr2 = real-ub(element-type-desc) in
               R ⟦ expr2 ⟧ (t)(p)(k2)(v1)(stk1)
```

```
                where
                k2 = λ(e2,f2),v2,stk2.
                        mk-array-signal-dec-post-init-elt-arrays-to
                           (signal-duqn*)(driver-duqn*)(e)(type-desc)
                           (lower-bound)(upper-bound)(element-type-desc)
                           (direction(element-type-desc))(e1)(e2)(t)(p)(v2)(stk2),
    mk-array-signal-dec-post-init-elt-scalars-to
       (signal-duqn*)(driver-duqn*)(e)(type-desc)(lower-bound)(upper-bound)
       (element-type-desc)(element-waveform-type-desc)(t)(p)(v)(stk))

mk-array-signal-dec-post-init-downto(signal-duqn*)(driver-duqn*)(e
                                     (type-desc)(lower-bound)(upper-bound)
                                     (element-type-desc)(element-waveform-type-desc)
                                     (t)(p)(v)(stk)
= (is-array-tdesc?(element-type-desc)
    → let expr1 = real-lb(element-type-desc) in
        R [[ expr1 ]] (t)(p)(k1)(v)(stk)
        where
        k1 = λ(e1,f1),v1,stk1.
               let expr2 = real-ub(element-type-desc) in
                R [[ expr2 ]] (t)(p)(k2)(v1)(stk1)
                where
                k2 = λ(e2,f2),v2,stk2.
                        mk-array-signal-dec-post-init-elt-arrays-downto
                           (signal-duqn*)(driver-duqn*)(e)(type-desc)
                           (lower-bound)(upper-bound)(element-type-desc)
                           (direction(element-type-desc))(e1)(e2)(t)(p)(v2)(stk2),
    mk-array-signal-dec-post-init-elt-scalars-downto
       (signal-duqn*)(driver-duqn*)(e)(type-desc)(lower-bound)(upper-bound)
       (element-type-desc)(element-waveform-type-desc)(t)(p)(v)(stk))

mk-array-signal-dec-post-init-elt-arrays-to(signal-duqn*)(driver-duqn*)(e)
                                           (type-desc)(lower-bound)(upper-bound)
                                           (elt-type-desc)(elt-direction)(elt-lower-bound)(elt-upper-bound)
                                           (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
    let signal-duqn = hd(signal-duqn*)
        and driver-duqn = hd(driver-duqn*) in
     nconc
        (let signal-elts = mk-slice-elt-names-to
                              (signal-duqn)(lower-bound)(upper-bound)
             and driver-elts = mk-slice-elt-names-to
                                  (driver-duqn)(lower-bound)(upper-bound) in
          mk-array-signal-dec-post-init-aux
             (signal-elts)(driver-elts)(e)(elt-type-desc)(elt-direction)
             (elt-lower-bound)(elt-upper-bound)(elty(elt-type-desc))
             (waveform-type-desc(elty(elt-type-desc)))(t)(p)(v)(stk),
        mk-array-signal-dec-post-init-elt-arrays-to
           (tl(signal-duqn*))(tl(driver-duqn*))(tl(e))(type-desc)(lower-bound)
           (upper-bound)(elt-type-desc)(elt-direction)(elt-lower-bound)
           (elt-upper-bound)(t)(p)(v)(stk)))

mk-array-signal-dec-post-init-elt-arrays-downto(signal-duqn*)(driver-duqn*)(e)
                                               (type-desc)(lower-bound)(upper-bound)
                                               (elt-type-desc)(elt-direction)(elt-lower-bound)(elt-upper-bound)
                                               (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
```

```
    let signal-duqn = hd(signal-duqn*)
        and driver-duqn = hd(driver-duqn*) in
     nconc
        (let signal-elts = mk-slice-elt-names-downto
                              (signal-duqn)(lower-bound)(upper-bound)
            and driver-elts = mk-slice-elt-names-downto
                                 (driver-duqn)(lower-bound)(upper-bound) in
          mk-array-signal-dec-post-init-aux
            (signal-elts)(driver-elts)(e)(elt-type-desc)(elt-direction)
            (elt-lower-bound)(elt-upper-bound)(elty(elt-type-desc))
            (waveform-type-desc(elty(elt-type-desc)))(t)(p)(v)(stk),
        mk-array-signal-dec-post-init-elt-arrays-downto
          (tl(signal-duqn*))(tl(driver-duqn*))(tl(e))(type-desc)(lower-bound)
          (upper-bound)(elt-type-desc)(elt-direction)(elt-lower-bound)
          (elt-upper-bound)(t)(p)(v)(stk)))

mk-array-signal-dec-post-init-aux(signal-duqn*)(driver-duqn*)(e)
                                 (type-desc)(direction)(lower-bound)(upper-bound)
                                 (element-type-desc)(element-waveform-type-desc)
                                 (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
    let signal-duqn = hd(signal-duqn*)
        and driver-duqn = hd(driver-duqn*) in
     nconc
        (mk-array-signal-dec-post-init
            ((signal-duqn))((driver-duqn))(hd(e))(type-desc)(direction)
            (lower-bound)(upper-bound)(element-type-desc)(element-waveform-type-desc)
            (t)(p)(v)(stk),
        mk-array-signal-dec-post-init-aux
          (tl(signal-duqn*))(tl(driver-duqn*))(tl(e))(type-desc)(direction)
          (lower-bound)(upper-bound)(element-type-desc)(element-waveform-type-desc)
          (t)(p)(v)(stk)))

mk-array-signal-dec-post-init-elt-scalars-to(signal-duqn*)(driver-duqn*)(e)
                                        (type-desc)(lower-bound)(upper-bound)
                                        (element-type-desc)(element-waveform-type-desc)
                                        (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
    let signal-duqn = hd(signal-duqn*)
        and driver-duqn = hd(driver-duqn*) in
     let initial-waveforms = init-array-signal-to
                                (signal-duqn)(driver-duqn)(e)(type-desc)
                                (element-type-desc)(lower-bound)(upper-bound) in
      nconc
        (assign-array-to
            (driver-duqn)(initial-waveforms)(element-waveform-type-desc)
            (lower-bound)(0),
         mk-array-signal-dec-post-init-elt-scalars-to
           (tl(signal-duqn*))(tl(driver-duqn*))(e)(type-desc)(lower-bound)
           (upper-bound)(element-type-desc)(element-waveform-type-desc)(t)(p)(v)
           (stk)))

mk-array-signal-dec-post-init-elt-scalars-downto(signal-duqn*)(driver-duqn*)(e)
                                           (type-desc)(lower-bound)(upper-bound)
                                           (element-type-desc)(element-waveform-type-desc)
                                           (t)(p)(v)(stk)
= (null(signal-duqn*)→ ε,
```

```
  let signal-duqn = hd(signal-duqn*)
      and driver-duqn = hd(driver-duqn*) in
   let initial-waveforms = init-array-signal-downto
                              (signal-duqn)(driver-duqn)(e)(type-desc)
                              (element-type-desc)(lower-bound)(upper-bound) in
     nconc
        (assign-array-downto
            (driver-duqn)(initial-waveforms)(element-waveform-type-desc)
            (upper-bound)(0),
        mk-array-signal-dec-post-init-elt-scalars-downto
           (tl(signal-duqn*))(tl(driver-duqn*))(e)(type-desc)(lower-bound)
           (upper-bound)(element-type-desc)(element-waveform-type-desc)(t)(p)(v)
           (stk)))
```

(D7) $\underline{\mathbf{D}}$ ⟦ **ETDEC** id id^+ ⟧ (t)(p)(u)(v)(stk)
= (mk-decl-sd
(hd(p))(ε)(ε)(ε)
(nconc(mk-etdec-post((id))(t)(p),u(v)(stk))))

```
mk-etdec-post(type-mark)(t)(p)
= let d = lookup-desc(type-mark)(t)(p) in
    mk-enumlit-rels(d)(literals(d))

mk-enumlit-rels(d)(id*)
= (null(tl(id*))→ ε,
   let id1 = hd(id*)
       and id2 = hd(tl(id*)) in
    cons(mk-rel(d)((PRED ,id1,id2)),mk-enumlit-rels(d)(tl(id*))))
```

The translation of an enumeration type declaration emits an SDVS declaration of the enumeration type.

(D8) $\underline{\mathbf{D}}$ ⟦ **ATDEC** id discrete-range type-mark ⟧ (t)(p)(u)(v)(stk)
= **let** (direction,$expr_1$,$expr_2$) = discrete-range **in**
let lower-bound = (direction = **TO** → $expr_1$, $expr_2$)
and upper-bound = (direction = **TO** → $expr_2$, $expr_1$) **in**
attributes-low-high
((id,lower-bound,upper-bound,(**UNIVERSAL_INTEGER**)))(t)(p)(u)(v)(stk)

```
attributes-low-high(id,lower-bound,upper-bound,attribute-type-mark)(t)(p)(u)(v)(stk)
= let decl1 = (DEC ,SYSGEN ,(mk-tick-low(id)),attribute-type-mark,lower-bound)
      and decl2 = (DEC ,SYSGEN ,(mk-tick-high(id)),attribute-type-mark,upper-bound) in
    let decl+ = (decl1,decl2) in
     D ⟦ decl+ ⟧ (t)(p)(u)(v)(stk)

mk-tick-low(id) = catenate(id,"'LOW")

mk-tick-high(id) = catenate(id,"'HIGH")
```

An array type declaration declares and initializes the `'low` and `'high` array type attributes.

(D9) $\underline{\mathbf{D}}$ ⟦ **PACKAGE** id decl* opt-id ⟧ (t)(p)(u)(v)(stk)
= $\underline{\mathbf{D}}$ ⟦ decl* ⟧ (t)(%(p)(id))(u)(v)(stk)

The declarations contained within a package are translated as usual, but in the package's context in the TSE, via the extended path **%(p)(id)**.

```
(D10) D [[ PACKAGEBODY id decl* opt-id ]] (t)(p)(u)(v)(stk)
      = let pb-exit-desc = <*PACKAGE-BODY-EXIT* ,id,p,λv,s.u(v)(s)> in
          D [[ decl* ]] (t)(%(p)(id))(u1)(v)(stk-push(pb-exit-desc)(stk))
            where u1 = λv1,stk1.pkg-body-exit(v1)(stk1)

pkg-body-exit(v)(stk)
= let <tg,qname,p,g> = hd(stk) in
    (case tg
       *STKBOTTOM* → model-execution-complete(qname),
       *UNDECLARE* → g(λvv,s.pkg-body-exit(vv)(s))(v)(stk),
       (*BEGIN* ) → pkg-body-exit(v)(stk-pop(stk)),
       (*PACKAGE-BODY-EXIT* ,*LOOP-EXIT* ,*SUBPROGRAM-RETURN* ) → g(v)(stk-pop(stk)),
       OTHERWISE
       → impl-error("Unknown execution stack descriptor with tag: ~a",tg))
```

The declarations contained in a package body are translated in the package's context in the TSE, via the extended path **%(p)(id)**. A ***PACKAGE-BODY-EXIT*** descriptor is first pushed onto the execution stack to prevent the package's declarations from being unelaborated when the package body is exited.

```
(D11) D [[ PROCEDURE id proc-par-spec* ]] (t)(p)(u)(v)(stk) = u(v)(stk)

(D12) D [[ FUNCTION id func-par-spec* type-mark ]] (t)(p)(u)(v)(stk) = u(v)(stk)

(D13) D [[ SUBPROGBODY subprog-spec decl* seq-stat* opt-id ]] (t)(p)(u)(v)(stk)
      = u(v)(stk)
```

Subprogram declarations need no Phase 2 translation, nor do subprogram bodies.

```
(D14) D [[ USE dotted-name+ ]] (t)(p)(u)(v)(stk) = u(v)(stk)
```

The effect of USE clauses has already been recorded in the TSE during Phase 1; no further Phase 2 translation is necessary.

```
(D15) D [[ STDEC id type-mark opt-discrete-range ]] (t)(p)(u)(v)(stk)
      = let z = hd(p)
            and subtype-desc = lookup-desc-on-path(t)(p)(id) in
        let basetype-desc = base-type(subtype-desc) in
          let expr1 = type-tick-low(basetype-desc)
              and expr2 = type-tick-low(subtype-desc)
              and expr3 = type-tick-high(subtype-desc)
              and expr4 = type-tick-high(basetype-desc) in
            R [[ expr1 ]] (t)(p)(k1)(v)(stk)
              where
              k1 = λ(e1,f1),v1,stk1.
                     R [[ expr2 ]] (t)(p)(k2)(v1)(stk1)
                       where
                       k2 = λ(e2,f2),v2,stk2.
                              R [[ expr3 ]] (t)(p)(k3)(v2)(stk2)
                                where
```

```
k3 = λ(e3,f3),v3,stk3.
       R ⟦ expr4 ⟧ (t)(p)(k4)(v3)(stk3)
        where
        k4 = λ(e4,f4),v4,stk4.
               (mk-decl-sd
                  (z)
                  (nconc
                     ((e1
                       → (mk-rel
                             (basetype-desc)
                             ((LE ,e1,e2))),
                       ε),
                      (e4
                       → (mk-rel
                             (basetype-desc)
                             ((LE ,e3,e4))),
                       ε)))(ε)(ε)
                  (u1(v4)(stk4)))
             where
             u1 = λv5,stk5.
                    attributes-low-high
                       ((id,expr2,expr3,
                         (idf(basetype-desc))))(t)(p)(u)
                       (v5)(stk5)
```

The Phase 2 semantics of subtype declarations generates a state delta with guards in the precondition to ensure that the subtype range falls within the range of allowable values for the subtype's base type. Assuming this holds, the continuation in the state delta's postcondition performs the Phase 2 processing of declarations and initializations for the `'low` and `'high` attributes representing the subtype bounds.

```
(D16) D ⟦ ITDEC id discrete-range ⟧ (t)(p)(u)(v)(stk)
      = let  z = hd(p)
             and integer-type-desc = lookup-desc-on-path(t)(p)(id)  in
        let  expr1 = type-tick-low(integer-type-desc)
             and expr2 = type-tick-high(integer-type-desc)  in
         attributes-low-high
            ((id,expr1,expr2,(UNIVERSAL_INTEGER) ))(t)(p)(u)(v)(stk)
```

The Phase 2 semantics of integer type declarations simply processes declarations and initializations for the `'low` and `'high` attributes representing the integer type bounds.

8.4.5 Concurrent Statements

```
(CS0) CS ⟦ ε ⟧ (t)(p)(u)(v)(stk) = u(v)(stk)
```

```
(CS1) CS ⟦ con-stat con-stat* ⟧ (t)(p)(u)(v)(stk)
      = CS ⟦ con-stat ⟧ (t)(p)(u1)(v)(stk)
          where u1 = λv,stk.CS ⟦ con-stat* ⟧ (t)(p)(u)(v)(stk)
```

A list of concurrent statements is translated in order, from first to last.

```
(CS2) CS [[ PROCESS id decl* seq-stat* opt-id phase1-hook ]] (t)(p)(u)(v)(stk)
      = let p1 = %(p)(id) in
          (mk-decl-sd
             (hd(p))(ε)(ε)(ε)
             ((make-vhdl-process-elaborate(id)(t)(p1)(seq-stat*)(u1)(v)(stk))))
        where u1 = λv,stk.D [[ decl* ]] (t)(p1)(u)(v)(stk)
```

8.4.6 Sequential Statements

```
(SS0) SS [[ ε ]] (t)(p)(c)(v)(stk) = c(v)(stk)
```

```
(SS1) SS [[ seq-stat seq-stat* ]] (t)(p)(c)(v)(stk)
      = SS [[ seq-stat ]] (t)(p)(c1)(v)(stk)
        where c1 = λv,stk.SS [[ seq-stat* ]] (t)(p)(c)(v)(stk)
```

A list of sequential statements is translated in order, from first to last.

```
(SS2) SS [[ NULL atmark ]] (t)(p)(c)(v)(stk)
      = ((EQ ,pound(catenate(hd(p),"\pc")),atmark),
         mk-sd(hd(p))(ε)(ε)(ε)(c(v)(stk)))
```

NULL statements have no effect.

```
(SS3) SS [[ VARASSN atmark ref expr ]] (t)(p)(c)(v)(stk)
      = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
        let d = T [[ ref ]] (t)(p) in
         E [[ ref ]] (t)(p)(k1)(v)(stk)
          where
          k1 = λ(e1,f1),v,stk.
                R [[ expr ]] (t)(p)(k2)(v)(stk)
                 where
                 k2 = λ(e2,f2),v,stk.
                       let precondition = nconc(f1,f2) in
                        (mk-sd
                           (hd(p))(precondition)(ε)((e1))
                           (nconc
                              (assign(d)((e1,e2)),
                              c(v)(stk)))))
```

```
assign(d)(target,value)
= (case tag(d)
     (*BOOL* ,*BIT* ,*INT* ,*REAL* ,*TIME* ,*VHDLTIME* ,*ENUMTYPE* ,*WAVE* ,
      *VOID* ,*POLY* )
     → (mk-rel(d)((EQ ,pound(target),value))),
     *SUBTYPE* → assign(base-type(d))((target,value)),
     *INT_TYPE* → assign(parent-type(d))((target,value)),
     *ARRAYTYPE*
     → (is-bitvector-tdesc?(d)
        → (is-constant-bitvector?(value)
           → (case direction(d)
                TO
                → assign-array-to
```

```
                (target)(value)(elty(d))((ORIGIN ,target))(0),
            DOWNTO
            → assign-array-downto
                (target)(value)(elty(d))
                (mk-exp2
                    (SUB ,
                    mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),1))(0),
            OTHERWISE → impl-error("Illegal direction: ~a",direction
                                                                (d))),
        (mk-rel(d)((EQ ,pound(target),value)))),
    is-string-tdesc?(d)
    → (is-constant-string?(value)
        → (case direction(d)
            TO
            → assign-array-to
                (target)(value)(elty(d))((ORIGIN ,target))(0),
            DOWNTO
            → assign-array-downto
                (target)(value)(elty(d))
                (mk-exp2
                    (SUB ,
                    mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),1))(0),
            OTHERWISE → impl-error("Illegal direction: ~a",direction
                                                                (d))),
        (mk-rel(d)((EQ ,pound(target),value)))),
    (dotted-expr-p(value)→ (mk-rel(d)((EQ ,pound(target),value))),
     (case direction(d)
        TO → assign-array-to(target)(value)(elty(d))((ORIGIN ,target))(0),
        DOWNTO
        → assign-array-downto
            (target)(value)(elty(d))
            (mk-exp2
                (SUB ,mk-exp2(ADD ,(ORIGIN ,target),(RANGE ,target)),
                1))(0),
        OTHERWISE → impl-error("Illegal direction: ~a",direction(d))))),
*RECORDTYPE*
→ (dotted-expr-p(value)→ assign-record(d)((target,value)),
    assign-record-fields(components(d))((target,value))),
OTHERWISE → impl-error("Unrecognized Stage 3 VHDL type tag: ~a",tag(d)))
```

The translation of a variable assignment statement first translates its left and right parts, obtaining translated expressions and guard formulas. Note that the left part is translated by **E** and is therefore not dereferenced (by application of the **dot** function), as it would be if **R** were used instead. The precondition of the generated state delta consists of the combined lists of guard formulas, and its mod list is the translated left part. Its postcondition asserts the new value of the left part place, and then asserts succeeding state deltas by appropriately using the continuation **c**. Assignments in Stage 3 VHDL can be scalar or can assign entire arrays. Entire array assignments are asserted element by element via auxiliary semantic function **array-signal-assignment**.

```
(SS4) SS ⟦ SIGASSN atmark delay-type ref waveform ⟧ (t)(p)(c)(v)(stk)
      = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
        let d = T ⟦ ref ⟧ (t)(p) in
          (case tag(d)
```

```
        (*BOOL* ,*BIT* ,*INT* ,*REAL* ,*TIME* ,*ENUMTYPE* ,*SUBTYPE* ,
         *INT_TYPE* )
        → scalar-signal-assignment
              (seq-stat)(delay-type)(ref)(waveform)(d)(t)(p)(c)(v)(stk),
        *ARRAYTYPE*
        → array-signal-assignment
              (atmark)(delay-type)(ref)(waveform)(t)(p)(c)(v)(stk),
        OTHERWISE
        → impl-error
              ("Signal assignment not implemented for object ",ref,
              " of type ",d)))
scalar-signal-assignment(seq-stat)(delay-type)(ref)(waveform)(d)(t)(p)(c)(v)(stk)
= E [[ ref ]] (t)(p)(k)(v)(stk)
    where
    k = λ(signal-name,guard),v,stk.
          let driver-name = name-driver(signal-name) in
           W [[ waveform ]] (t)(p)(wave-cont)(v)(stk)
            where
            wave-cont = λ(trans*,guard*),v,stk.
                        let all-guards = nconc(guard,guard*) in
                         (delay-type = TRANSPORT
                          → (mk-sd
                                (hd(p))(all-guards)(ε)((driver-name))
                                (nconc
                                    (assign
                                        (waveform-type-desc(d))
                                        ((driver-name,
                                          mk-transport-update
                                              (dot(driver-name))(trans*))),
                                      c(v)(stk)))),
                           let earliest-new-transaction = hd(trans*) in
                            (mk-sd
                                (hd(p))
                                (cons(mk-preemption
                                          (dot(driver-name))
                                          (earliest-new-transaction),all-guards))(ε)((driver-name))
                                (nconc
                                    (assign
                                        (waveform-type-desc(d))
                                        ((driver-name,
                                          mk-inertial-update
                                              (dot(driver-name))(trans*))),
                                      c(v)(stk))),
                             mk-sd
                                (hd(p))
                                (cons(mk-not
                                          (mk-preemption
                                              (dot(driver-name))
                                              (earliest-new-transaction)),
                                 all-guards))(ε)((driver-name))
                                (nconc
                                    (assign
                                        (waveform-type-desc(d))
                                        ((driver-name,
                                          mk-inertial-update
                                              (dot(driver-name))(trans*))),
                                      c(v)(stk)))))
```

```
waveform-type-desc(type-desc) = <WAVEFORM ,ε,*WAVE* ,(STANDARD) ,tt,type-desc>

mk-transport-update(dot-driver)(trans*)
= cons(TRANSPORT_UPDATE ,cons(dot-driver,trans*))

mk-preemption(dot-driver)(transaction)
= (PREEMPTION ,dot-driver,transaction)

mk-inertial-update(dot-driver)(trans*)
= cons(INERTIAL_UPDATE ,cons(dot-driver,trans*))

mk-not(e) = (NOT ,e)


array-signal-assignment(atmark)(delay-type)(ref)(waveform)(t)(p)(c)(v)(stk)
= let seq-stat+ = cascade-array-signal-assignment
                    (atmark)(delay-type)(ref)(waveform)(t)(p)(c)(v)(stk) in
    SS ⟦ seq-stat+ ⟧ (t)(p)(c)(v)(stk)

cascade-array-signal-assignment(atmark)(delay-type)(ref)(agg-wave)(t)(p)(c)(v)(stk)
= let array-refs = mk-array-refs(ref)(t)(p)(c)(v)(stk)
      and element-waves = mk-element-waves(agg-wave)(t)(p)(c)(v)(stk) in
    mk-scalar-signal-assignments(atmark)(delay-type)(array-refs)(element-waves)

mk-scalar-signal-assignments(atmark)(delay-type)(array-refs)(element-waves)
= (null(array-refs)→ ε,
   cons((SIGASSN ,atmark,delay-type,hd(array-refs),hd(element-waves)),
   mk-scalar-signal-assignments
     (atmark)(delay-type)(tl(array-refs))(tl(element-waves))))

mk-array-refs(ref)(t)(p)(c)(v)(stk)
= let d = T ⟦ ref ⟧ (t)(p) in
    let direction = direction(d)
        and expr1 = lb(d)
        and expr2 = ub(d) in
      R ⟦ expr1 ⟧ (t)(p)(k1)(v)(stk)
       where
       k1 = λ(e1,f1),v1,stk1.
              R ⟦ expr2 ⟧ (t)(p)(k2)(v1)(stk1)
               where
               k2 = λ(e2,f2),v2,stk2.
                      let sref = hd(second(ref))
                          and indices = (direction = TO
                                          → gen-ascending-indices(e1)(e2),
                                          gen-descending-indices(e1)(e2)) in
                        mk-array-refs-aux(sref)(indices)

gen-ascending-indices(min)(max)
= (min > max → ε, cons(min,gen-ascending-indices(min+1)(max)))

gen-descending-indices(min)(max)
= (max < min → ε, cons(max,gen-descending-indices(min)(max−1)))

mk-array-refs-aux(sref)(indices)
= (null(indices)→ ε,
   cons((REF ,(sref,(INDEX ,(NUM ,hd(indices))))),
   mk-array-refs-aux(sref)(tl(indices))))
```

```
mk-element-waves(agg-wave)(t)(p)(c)(v)(stk)
= let aggregate-transactions = second(agg-wave) in
    let element-transaction-lists = mk-element-transaction-lists
                                    (aggregate-transactions)(t)(p)(c)(v)(stk) in
     mk-element-waves-aux(element-transaction-lists)

mk-element-transaction-lists(aggregate-transactions)(t)(p)(c)(v)(stk)
= (null(aggregate-transactions)→ ε,
   cons(mk-transaction-list(hd(aggregate-transactions))(t)(p)(c)(v)(stk),
   mk-element-transaction-lists(tl(aggregate-transactions))(t)(p)(c)(v)(stk)))

mk-transaction-list(agg-trans)(t)(p)(c)(v)(stk)
= let agg-value-expr = second(agg-trans)
      and time-expr = third(agg-trans) in
    let element-value-exprs = (case hd(agg-value-expr)
                                REF
                                → mk-array-refs(agg-value-expr)(t)(p)(c)(v)(stk),
                                (BITSTR ,STR ,PAGGR ) → hd(tl(agg-value-expr)),
                                OTHERWISE
                                → impl-error
                                     ("Illegal aggregate in transaction: ",
                                     agg-value-expr)) in
     mk-simultaneous-transactions(element-value-exprs)(time-expr)

mk-simultaneous-transactions(expr*)(time-expr)
= (null(expr*)→ ε,
   cons((TRANS ,hd(expr*),time-expr),
   mk-simultaneous-transactions(tl(expr*))(time-expr)))


(SS5) SS ⟦ IF atmark cond-part+ else-part ⟧ (t)(p)(c)(v)(stk)
      = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
        let seq-stat* = else-part in
         gen-if(cond-part+)(seq-stat*)(seq-stat)(t)(p)(c)(v)(stk))

gen-if(cond-part*)(seq-stat*)(ifclause)(t)(p)(c)(v)(stk)
= (null(cond-part*)→ SS ⟦ seq-stat* ⟧ (t)(p)(c)(v)(stk),
   let (expr,seq-stat1*) = hd(cond-part*) in
    R ⟦ expr ⟧ (t)(p)(k)(v)(stk)
     where
     k = λ(e,f),v1,stk1.
          (mk-sd
             (hd(p))(cons(e,f))(ε)(ε)
             (let c1 = λv2,stk2.SS ⟦ seq-stat1* ⟧ (t)(p)(c)(v2)(stk2) in
               c1(v1)(stk1)),
           mk-sd
             (hd(p))(cons(mk-not(e),f))(ε)(ε)
             (let c2 = λv3,stk3.
                         gen-if
                           (tl(cond-part*))(seq-stat*)(ε)(t)(p)(c)(v3)(stk3) in
              c2(v1)(stk1))))
```

The abstract syntax of a Stage 3 VHDL `IF` statement consists of a finite, nonempty list of **cond-part**s followed by a (possibly empty) **else-part**. Each **cond-part** corresponds to an `IF expr THEN seq-stats` or an `ELSIF expr THEN seq-stats` construct in the concrete

syntax. Thus each **cond-part** must be translated into *two* state deltas: one for the case where **expr** evaluates to **true** and the other where it evaluates to **false**. The translation is performed by auxiliary semantic function **gen-if**, which takes as arguments (among others): the **cond-part** list and the **seq-stat**s comprising the **else-part**. Successive recursive calls of **gen-if** process the first element of their **cond-part** list, reducing it to empty. When the **cond-part** list is empty, **gen-if** produces the translation of the **else-part**. The function **mk-not** constructs the logical negation of its argument.

```
(SS6) SS ⟦ CASE atmark expr case-alt+ ⟧ (t)(p)(c)(v)(stk)
      = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
        R ⟦ expr ⟧ (t)(p)(k)(v)(stk)
         where
         k = λ(e,f),v,stk.
               let d = T ⟦ expr ⟧ (t)(p) in
                 gen-case(ε)(d)((e,f))(case-alt+)(t)(p)(c)(v)(stk))

gen-case(g)(d)(e,f)(case-alt*)(t)(p)(c)(v)(stk)
= (null(case-alt*)→ ε,
   let (h,sd) = gen-alt(g)(d)((e,f))(hd(case-alt*))(t)(p)(c)(v)(stk) in
    cons(sd,gen-case(append(g,h))(d)((e,f))(tl(case-alt*))(t)(p)(c)(v)(stk)))

gen-alt(g)(d)(e,f)(case-alt)(t)(p)(c)(v)(stk)
= let case-alt-tag = hd(case-alt) in
   (case-alt-tag = CASEOTHERS
    → let seq-stat* = hd(tl(case-alt)) in
        let c1 = λv1,stk1.SS ⟦ seq-stat* ⟧ (t)(p)(c)(v1)(stk1) in
         (ε,
          mk-sd
             (hd(p))(append(f,(mk-not(mk-ors(g)))))(ε)(ε)
             (c1(v)(stk))),
    let (case-set,seq-stat*) = tl(case-alt) in
     let c1 = λv1,stk1.SS ⟦ seq-stat* ⟧ (t)(p)(c)(v1)(stk1) in
      let h = append(f,gen-guard(case-set)(d)(e)(t)(p)) in
       (h,mk-sd(hd(p))(h)(ε)(ε)(c1(v)(stk))))

mk-ors(disjs)
= (case length(disjs)
     1 → hd(disjs),
     2 → mk-or(hd(disjs))(hd(tl(disjs))),
     OTHERWISE → mk-or(hd(disjs))(mk-ors(tl(disjs))))

mk-or(e1,e2)
= (null(e1)→ e2,
   null(e2)→ e1,
   consp(e1)∧ consp(e2)
   → (hd(e1)= OR
      → (hd(e2)= OR → cons(OR ,append(tl(e1),tl(e2))), append(e1,(e2))),
      hd(e2)= OR → nconc((OR ,e1),tl(e2)),
      (OR ,e1,e2)),
   (OR ,e1,e2))

gen-guard(discrete-range*)(d)(e)(t)(p)
= (null(discrete-range*)→ ε,
   let (direction,expr1,expr2) = hd(discrete-range*) in
    R ⟦ expr1 ⟧ (t)(p)(k1)(ε)(ε)
```

```
where
k1 = λ(e1,f1),v1,stk1.
       (expr1 = expr2
        → let h = nconc(f1,(mk-rel(d)((EQ ,e,e1)))) in
            (null(tl(discrete-range*))→ h,
             (cons(OR ,
              cons(hd(h),gen-guard(tl(discrete-range*))(d)(e)(t)(p))))),
        R [[ expr2 ]] (t)(p)(k2)(v1)(stk1)
         where
         k2 = λ(e2,f2),v2,stk2.
                let h = nconc
                            (f1,f2,
                            (direction = TO
                             → ((AND ,mk-rel(d)((GE ,e,e1)),
                                  mk-rel(d)((LE ,e,e2)))),
                             ((AND ,mk-rel(d)((LE ,e,e1)),
                               mk-rel(d)((GE ,e,e2)))))) in
                 (cons(OR ,
                  cons(hd(h),
                  gen-guard(tl(discrete-range*))(d)(e)(t)(p))))))
```

The abstract syntax of a CASE statement consists of a selector expression followed by a finite, nonempty list of case alternatives. Each case alternative consists of a list of sequential statements, preceded either by a nonempty list of discrete ranges (indicated by CASECHOICE) or (for the last alternative only) by CASEOTHERS. Each of these discrete range lists represents a set of values, called a *case selection set*. If the selector expression evaluates to one of these values, then the corresponding sequential statement list is executed, after which control passes to the successor of the CASE statement. CASEOTHERS represents a case selection set that is the complement of the union of all of the other case selection sets relative to the set of values in the selector expression's type. Phase 1 has ensured that no case selection sets intersect.

The Phase 2 translation of a CASE statement first processes its selector expression, obtaining a translated expression and a guard formula. The translation is completed by the function **gen-case**, which takes the following arguments:

- a formula, initially empty, that is the disjunction of formulas representing the case selection sets of case alternatives translated so far in this CASE statement — this formula's negation represents the case selection set indicated by CASEOTHERS (if present) in the CASE statement;
- the basic type of the selector expression (and the case selection set elements);
- the selector expression's translation and guard formula; and
- a list of case alternatives.

Each successive recursive call to **gen-case** processes the first element of its case alternative list, reducing the list to empty, at which time processing terminates normally. Each case alternative is processed by auxiliary semantic function **gen-alt**, which returns a formula

representing the case selection set for that alternative and a state delta representing the execution of the corresponding sequential statement list. This formula and state delta are collected by **gen-case**; the final result returned by **gen-case** is a list of state deltas. The function **gen-guard** converts discrete range lists into formulas representing case selection sets. The function **mk-or(formula$_1$, formula$_2$)** constructs the logical disjunction of two formulas; if one of the formulas is empty, then **mk-or** ignores it and returns the nonempty one.

```
(SS7) SS [[ LOOP atmark id seq-stat* opt-id ]] (t)(p)(c)(v)(stk)
      = let lp-desc = <*LOOP-EXIT* ,id,p,λv,s.c(v)(s)> in
          let stk1 = stk-push(lp-desc)(stk) in
            cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
            loop-infinite(seq-stat)(id)(seq-stat*)(t)(%(p)(id))(c)(v)(stk1))

loop-infinite(seq-stat)(id)(seq-stat*)(t)(p)(c)(v)(stk)
= let c1 = λv,stk.
             SS [[ seq-stat* ]] (t)(p)(c2)(v)(stk)
               where
               c2 = λv,stk.
                      loop-infinite(seq-stat)(id)(seq-stat*)(t)(p)(c)(v)(stk) in
  (mk-sd(hd(p))(ε)(ε)(ε)(c1(v)(stk)))


(SS8) SS [[ WHILE atmark id expr seq-stat* opt-id ]] (t)(p)(c)(v)(stk)
      = let lp-desc = <*LOOP-EXIT* ,id,p,λv,s.c(v)(s)> in
          let stk1 = stk-push(lp-desc)(stk) in
            cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
            loop-while(seq-stat)(id)(expr)(seq-stat*)(t)(%(p)(id))(c)(v)(stk1))

loop-while(seq-stat)(id)(expr)(seq-stat*)(t)(p)(c)(v)(stk)
= R [[ expr ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v,stk.
          let c1 = λv,stk.
                     SS [[ seq-stat* ]] (t)(p)(c2)(v)(stk)
                       where
                       c2 = λv,stk.
                              loop-while
                                 (seq-stat)(id)(expr)(seq-stat*)(t)(p)(c)(v)
                                 (stk) in
            (mk-sd
               (hd(p))(cons(e,f))(ε)(ε)(c1(v)(stk)),
             mk-sd
               (hd(p))(cons(mk-not(e),f))(ε)(ε)
               (c(v)(stk-pop(stk))))


(SS9) SS [[ FOR atmark id ref discrete-range seq-stat* opt-id ]] (t)(p)(c)(v)(stk)
      = let d = T [[ ref ]] (t)(p) in
          let lp-desc = <*LOOP-EXIT* ,id,p,
                          λv,s.c(v)(s)> in
           let stk0 = stk-push(lp-desc)(stk) in
            let (direction,expr1,expr2) = discrete-range in
             cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
             R [[ expr1 ]] (t)(p)(k1)(v)(stk)
```

```
where
k1 = λ(e1,f1),v1,stk1.
      R ⟦ expr2 ⟧ (t)(p)(k2)(v1)(stk1)
       where
       k2 = λ(e2,f2),v2,stk2.
            let bk-desc = <*BLOCK-EXIT* ,id,p,λv,s.c(v)(s)> in
             let decl = (DEC ,CONST ,
                         (last(hd(hd(tl(ref))))),
                         (hd(d)),hd(tl(discrete-range))) in
              D ⟦ decl ⟧ (t)(%(p)(id))(u)(v)
                 (stk-push(bk-desc)(stk0))
             where
             u = λv3,stk3.
                  let bg-desc = <*BEGIN* ,id,%(p)(id),
                                 λv,s.c1(v)(s)> in
                   (mk-sd
                      (hd(p))(nconc(f1,f2))(ε)(ε)
                      ((case tag(d)
                          *INT*
                          → let final-iter-val = eval-expr
                                                 (e2) in
                              loop-for-int
                                 (seq-stat)(ref)(d)
                                 (direction)
                                 (final-iter-val)
                                 (seq-stat*)(t)(%(p)(id))(c1)
                                 (v3)
                                 (stk-push(bg-desc)(stk3)),
                          *ENUMTYPE*
                          → let initial-iter-val = eval-expr
                                                   (e1)
                                 and final-iter-val = eval-expr
                                                      (e2)
                                 and enum-lits = literals
                                                 (d) in
                              let parameter-updates = tl(get-loop-enum-param-vals
                                                         (initial-iter-val)
                                                         (final-iter-val)
                                                         (direction)
                                                         (enum-lits)) in
                               loop-for-enum
                                  (seq-stat)(ref)(d)
                                  (direction)
                                  (parameter-updates)
                                  (final-iter-val)
                                  (seq-stat*)(t)(%(p)(id))
                                  (c1)(v3)
                                  (stk-push
                                     (bg-desc)(stk3)),
                          OTHERWISE
                          → impl-error
                               ("Illegal FOR loop parameter type: ~a",
                               d))))
                  where
                  c1 = λv4,stk4.
                       block-exit(v4)(stk4))
```

```
loop-for-int(seq-stat)(ref)(d)(direction)(final-iter-val)(seq-stat*)(t)(p)(c)(v)(stk)
= E [[ ref ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v,stk.
          R [[ ref ]] (t)(p)(k1)(v)(stk)
           where
           k1 = λ(e1,f1),v1,stk1.
                 let c0 = λv0,stk0.
                          SS [[ seq-stat* ]] (t)(p)(c1)(v0)(stk0)
                           where
                           c1 = λv2,stk2.
                                  (mk-sd
                                     (hd(p))(ε)(ε)((e))
                                     (cons(mk-rel
                                             (d)
                                             ((EQ ,pound(e),
                                               (direction = TO
                                                → mk-exp2(ADD ,e1,1),
                                                  mk-exp2(SUB ,e1,1)))),
                                      loop-for-int
                                        (seq-stat)(ref)(d)(direction)
                                        (final-iter-val)(seq-stat*)(t)
                                        (p)(c)(v2)(stk2)))) in
                    (mk-sd
                       (hd(p))
                       (cons(mk-rel
                               (d)
                               (((direction = TO → LE , GE ),e1,final-iter-val)),f1))(ε)(ε)(c0(v)(stk)),
                     mk-sd
                       (hd(p))
                       (cons(mk-rel
                               (d)
                               (((direction = TO → GT , LT ),e1,final-iter-val)),f1))(ε)(ε)
                       (c(v)(stk-pop(stk))))

loop-for-enum(seq-stat)(ref)(d)(direction)(parameter-updates)(final-iter-val)(seq-stat*)(t)(p)(c)(v)(stk)
= E [[ ref ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e,f),v,stk.
          R [[ ref ]] (t)(p)(k1)(v)(stk)
           where
           k1 = λ(e1,f1),v1,stk1.
                 let c0 = λv0,stk0.
                          SS [[ seq-stat* ]] (t)(p)(c1)(v0)(stk0)
                           where
                           c1 = λv2,stk2.
                                  (parameter-updates
                                   → (mk-sd
                                        (hd(p))(ε)(ε)((e))
                                        (cons(mk-rel
                                                (d)
                                                ((EQ ,pound(e),
                                                  hd(parameter-updates))),
                                         loop-for-enum
                                           (seq-stat)(ref)(d)
                                           (direction)
                                           (tl(parameter-updates))
```

```
                                    (final-iter-val)(seq-stat*)
                                    (t)(p)(c)(v2)(stk2)))),
                            (mk-sd
                               (hd(p))(ε)(ε)(ε)
                               (c(v)(stk-pop(stk))))) in
(mk-sd
   (hd(p))
   (cons(mk-rel
           (d)
           (((direction = TO → LE , GE ),e1,final-iter-val)),f1))(ε)(ε)(c0(v)(stk)),
 mk-sd
   (hd(p))
   (cons(mk-rel
           (d)
           (((direction = TO → GT , LT ),e1,final-iter-val)),f1))(ε)(ε)
   (c(v)(stk-pop(stk))))
```

A loop — i.e., a `LOOP`, `WHILE`, or `FOR` statement — has a label (used for leaving that loop by means of an `EXIT` statement) and a body consisting of sequential statements. When a loop is entered, a new local environment is created (signified by an extended path in the TSE), and a ***LOOP-EXIT*** descriptor is pushed onto the execution stack, to be used by `EXIT` statements to leave the loop properly. The continuation in the descriptor is that of the loop statement itself.

In the case of a simple `LOOP` statement, the loop is nonterminating, and a *recursive* state delta is generated by auxiliary semantic function **loop-infinite**.

In the case of a `WHILE` statement, auxiliary semantic function **loop-while** first processes the control expression, yielding its translation and a guard formula, and then uses these items to generate two state deltas, one of which is recursive. The recursive state delta represents the situation where the control expression is **true** and the loop's body is executed; recursion stems from the appearance of **loop-while** in the continuation of the loop body's translation. The execution stack remains unchanged in this case. The other state delta represents the case where the loop is exited "naturally" by virtue of its control expression having the value **false**. The postcondition of this state delta is the loop statement's continuation applied to the result of popping the loop statement's descriptor from the execution stack.

The case of a `FOR` statement is analogous to that of the `WHILE` statement, only more complex technically.

```
(SS10) SS [[ EXIT atmark opt-dotted-name opt-expr ]] (t)(p)(c)(v)(stk)
       = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
          let expr = opt-expr in
           R [[ expr ]] (t)(p)(k)(v)(stk)
           where
           k = λ(e,f),v1,stk1.
                 let loop-name = (null(opt-dotted-name)→ ε,
                                  last(opt-dotted-name)) in
            (null(e)→ exit(loop-name)(v1)(stk),
             (mk-sd
                (hd(p))(cons(e,f))(ε)(ε)
                (c1(v1)(stk1)
                  where c1 = λv2,stk2.exit(loop-name)(v2)(stk2)),
```

```
                    mk-sd
                      (hd(p))(cons(mk-not(e),f))(ε)(ε)
                      (c(v1)(stk1)))))

exit(loop-name)(v)(stk)
= let <tg,id,p,g> = hd(stk) in
    (case tg
      *LOOP-EXIT*
      → (¬null(loop-name)∧ id ≠ loop-name → exit(loop-name)(v)(stk-pop(stk)),
          g(v)(stk-pop(stk))),
      *UNDECLARE* → g(λvv,s.exit(loop-name)(vv)(s))(v)(stk),
      (*BEGIN* ,*BLOCK-EXIT* ) → exit(loop-name)(v)(stk-pop(stk)),
      OTHERWISE → execution-error("*** EXECUTION ERROR -- ILLEGAL EXIT ***"))
```

An EXIT statement:

- transfers control from the interior of a loop to the immediate successor of that loop, provided that the EXIT statement's condition (if any) is satisfied; and
- adjusts the state of SDVS to reflect that transfer of control.

The loop being exited can be named in the EXIT statement; Phase 1 has ensured that an appropriate label is used. If a loop is named, then that loop is exited. If no name appears, then the smallest loop enclosing the EXIT statement is exited. The EXIT statement may be enclosed within a system of nested loops. When the loop statement is exited, these other loops must first be exited in the order opposite that in which they were entered. When a FOR loop is exited, the effect of its implict local declaration of the iteration parameter is reversed by encountering an ***UNDECLARE*** descriptor on the execution stack.

The translation of an EXIT statement first processes its control expression (which may be empty), resulting in a translated expression and a guard formula. If the control expression is nonempty, two state deltas are generated. The first represents the case where the control expression has the value **true**; in this case the exit process proceeds by invoking the semantic function **exit**, which appears in the state delta's postcondition. The other state delta represents the case where the control expression has the value **false**, whereupon the exit does not occur and control passes to the immediate successor of the EXIT statement. If the control expression is empty, the exit is unconditional; the second state delta is not even generated.

```
(SS11) SS [[ CALL atmark ref ]] (t)(p)(c)(v)(stk)
       = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
          let basic-ref = second(ref) in
           let (tg,q,id) = hd(basic-ref) in
            let d = t(q)(id) in
             let expr* = second(second(basic-ref)) in
              gen-call(ref)(d)(expr*)(tt)(ff)(t)(p)(c)(v)(stk))

gen-call(ref)(d)(expr*)(gen-guards?)(no-unbind?)(t)(p)(c)(v)(stk)
= let z = hd(p)
      and q = %(path(d))(idf(d)) in
    let (decl*,seq-stat*) = body(d) in
```

```
bind-parameters(ref)(d)(expr*)(gen-guards?)(t)(p)(u)(v)(stk)
 where
 u = λv1,stk1.
      let sp-desc = <*SUBPROGRAM-RETURN* ,idf(d),p,λv,s.c(v)(s)>
          and par-desc = <*UNDECLARE* ,collect-allpars(extract-pars(d)(t)),p,
                                λc1,v4,stk4.
                                 (mk-sd
                                    (z)(ε)(ε)(ε)
                                    (cons((EQ ,pound(catenate(z,"\pc")),
                                           (EXITED ,$(path(d))(idf(d)))),
                                     unbind-parameters
                                       (ref)(d)(expr*)(no-unbind?)(t)(p)(c1)
                                       (v4)(stk4))),
                                  mk-sd
                                    (z)
                                    (((EQ ,dot(catenate(z,"\pc")),
                                       (EXITED ,$(path(d))(idf(d))))))(ε)(ε)
                                    (unbind-parameters
                                       (ref)(d)(expr*)(no-unbind?)(t)(p)(c1)(v4)
                                       (stk4)))> in
       let stk5 = stk-push(par-desc)(stk-push(sp-desc)(stk1)) in
        (mk-sd
           (z)(ε)(ε)(ε)
           (cons((EQ ,pound(catenate(z,"\pc")),
                  (AT ,$(path(d))(idf(d)))),
            u2(v1)(stk5))))
         where
         u2 = λv6,stk6.
                (null(characterizations(d))
                 → D [[ decl* ]] (t)(q)(u1)(v6)(stk6),
                 null(seq-stat*)
                 → gen-characterizations
                     (ε)(p)(characterizations(d))(c2)(v6)(stk6)
                   where
                   c2 = λv7,stk7.
                          unbind-parameters
                            (ref)(d)(expr*)(no-unbind?)(t)(p)(c3)
                            (v7)(stk7)
                   where c3 = λv8,stk8.block-exit(v8)(stk8),
                 impl-error
                    ("Offline Characterization not yet implemented
                      for procedures with nonempty bodies !"))
       where
       u1 = λv2,stk2.
             let bg-desc = <*BEGIN* ,idf(d),q,λvv,s.c1(vv)(s)> in
              SS [[ seq-stat* ]] (t)(q)(c1)(v2)(stk-push(bg-desc)(stk2))
              where c1 = λv3,stk3.block-exit(v3)(stk3)

gen-characterizations(sds)(p)(characterizations)(c)(v)(stk)
= (null(characterizations)→ fix-characterized-sds(sds)(c(v)(stk)),
   let (q,id,parnames,pre,mod) = hd(characterizations) in
    let post = sixth(hd(characterizations)) in
     gen-characterizations
       (cons(gen-characterization(hd(p))($(q)(id))(parnames)(pre)(mod)(post)(v),sds))
       (p)(tl(characterizations))(c)(v)(stk))

gen-characterization(z)(qid)(parnames)(pre)(mod)(post)(v)
```

```
= let sd = mk-sd
            (z)(((EQ ,dot(catenate(z,"\pc")),(AT ,qid))))(ε)(mod)
            (append
               (post,((EQ ,pound(catenate(z,"\pc")),(EXITED ,qid))))) in
   subst-vars(parnames)(v)(sd)

bind-parameters(ref)(d)(actuals)(gen-guards?)(t)(p)(u)(v)(stk)
= let z = hd(p)
      and q = %(path(d))(idf(d))
      and par-assoc-list = extract-pars(d)(t) in
   (null(par-assoc-list)→ u(v)(stk),
    let all-formals = get-qids(collect-allpars(par-assoc-list))(t)(q)
        and to-formals = get-qids(collect-topars(par-assoc-list))(t)(q)
        and type-descriptors = collect-topars-types(par-assoc-list)
        and from-actuals = collect-fromargs(actuals)(par-assoc-list) in
     let v0 = push-universe(v)(z)(all-formals) in
      let qual-all-formals = get-qualified-ids(all-formals)(v0)
          and qual-to-formals = get-qualified-ids(to-formals)(v0) in
       (mk-decl-sd
          (z)(ε)(ε)((z))
          (nconc
             (mk-qual-id-coverings(all-formals)(qual-all-formals)(z)(v)(t),
             mk-par-decls(q)(par-assoc-list)(p)(t)(v0),
             (null(qual-to-formals)→ u(v0)(stk),
              let expr* = from-actuals in
               MR [[ expr* ]] (t)(p)(h)(v0)(stk)
               where
               h = λ(e*,f*),v1,stk1.
                     u1(v1)(stk1)
                      where
                      u1 = λv2,stk2.
                            let precondition = (gen-guards?
                                                → nconc
                                                   (mk-constraint-guards
                                                      (e*)(type-descriptors)
                                                      (t)(p)(v2)(stk2),f*),
                                                f*) in
                             (mk-decl-sd
                                (z)(precondition)(ε)(qual-to-formals)
                                (nconc
                                   (assign-multiple
                                      (qual-to-formals)(type-descriptors)(e*),
                                   u(v2)(stk2)))))))))

extract-pars(d)(t)
= let signatures = signatures(d) in
    let signature = hd(signatures) in
     (null(tl(signatures))→ pars(signature),
      extract-poly-pars(pars(signature))(t))

extract-poly-pars(par-assoc-list)(t)
= (null(par-assoc-list)→ ε,
   let par = hd(par-assoc-list) in
    cons((hd(par),(hd(second(par)),poly-type-desc(t))),
    extract-poly-pars(tl(par-assoc-list))(t)))

collect-allpars(par-assoc-list)
= (null(par-assoc-list)→ ε,
   let (id,w) = hd(par-assoc-list) in
    cons(id,collect-allpars(tl(par-assoc-list))))
```

```
collect-topars(par-assoc-list)
= (null(par-assoc-list)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF VAL)
      → cons(id,collect-topars(tl(par-assoc-list))),
      collect-topars(tl(par-assoc-list))))

collect-fromargs(actuals)(par-assoc-list)
= (null(par-assoc-list)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF VAL)
      → cons(hd(actuals),collect-fromargs(tl(actuals))(tl(par-assoc-list))),
      collect-fromargs(tl(actuals))(tl(par-assoc-list))))

collect-frompars(par-assoc-list)(p)
= (null(par-assoc-list)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF OUT)
      → cons((REF ,((SREF ,p,id))),
         collect-frompars(tl(par-assoc-list))(p)),
      collect-frompars(tl(par-assoc-list))(p)))

collect-toargs(actuals-ids)(par-assoc-list)
= (null(actuals-ids)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF OUT)
      → cons(hd(actuals-ids),collect-toargs(tl(actuals-ids))(tl(par-assoc-list))),
      collect-toargs(tl(actuals-ids))(tl(par-assoc-list))))

collect-topars-types(par-assoc-list)
= (null(par-assoc-list)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF VAL)
      → cons(tdesc(w),collect-topars-types(tl(par-assoc-list))),
      collect-topars-types(tl(par-assoc-list))))

collect-toargs-types(actuals)(par-assoc-list)(t)(p)
= (null(actuals)→ ε,
    let (id,w) = hd(par-assoc-list) in
     (ref-mode(tmode(w))∈ (REF OUT)
      → let expr = hd(actuals) in
          cons(T ⟦ expr ⟧ (t)(p),
          collect-toargs-types(tl(actuals))(tl(par-assoc-list))(t)(p)),
      collect-toargs-types(tl(actuals))(tl(par-assoc-list))(t)(p)))

collect-guards-for-exprs(expr*)(d*)(t)(p)(v)(stk)
= MR ⟦ expr* ⟧ (t)(p)(h)(v)(stk)
    where h = λ(e*,f*),v,stk.mk-constraint-guards(e*)(d*)(t)(p)(v)(stk)

mk-constraint-guards(e*)(d*)(t)(p)(v)(stk)
= (null(e*)→ ε,
    let e = hd(e*)
        and d = hd(d*) in
     (¬(tag(d)∈ (*INT* *SUBTYPE* *INT_TYPE*) )
      → mk-constraint-guards(tl(e*))(tl(d*))(t)(p)(v)(stk),
      (tag(d)= *INT* → mk-constraint-guards(tl(e*))(tl(d*))(t)(p)(v)(stk),
       let dd = (tag(d)= *SUBTYPE* → base-type(d), parent-type(d))
```

```
          and expr1 = type-tick-low(d)
          and expr2 = type-tick-high(d)  in
        R [[ expr1 ]](t)(p)(k1)(v)(stk)
         where
         k1 = λ(e1,f1),v1,stk1.
                R [[ expr2 ]](t)(p)(k2)(v1)(stk1)
                 where
                 k2 = λ(e2,f2),v2,stk2.
                        nconc
                           ((e1 → (mk-rel(dd)((LE ,e1,e))), ε),
                           (e2 → (mk-rel(dd)((LE ,e,e2))), ε),
                           mk-constraint-guards(tl(e*))(tl(d*))(t)(p)(v)(stk)))))

mk-par-decls(q)(par-assoc-list)(p)(t)(v)
= (null(par-assoc-list)→ ε,
   let (id,w) = hd(par-assoc-list)  in
    cons((DECLARE ,qualified-id(qid(t(q)(id)))(v),mk-type-spec(tdesc(w))(t)(p)),
    mk-par-decls(q)(tl(par-assoc-list))(p)(t)(v)))

assign-multiple(duqn*)(type-descriptors)(e*)
= (null(duqn*)→ ε,
   let target = hd(duqn*)
       and d = hd(type-descriptors)
       and source = hd(e*)  in
    nconc
       (assign(d)((target,source)),
       assign-multiple(tl(duqn*))(tl(type-descriptors))(tl(e*))))

unbind-parameters(ref)(d)(actuals)(no-unbind?)(t)(p)(c)(v)(stk)
= let z = hd(p)
       and q = %(path(d))(idf(d))
       and par-assoc-list = extract-pars(d)(t)  in
    let all-formals = get-qids(collect-allpars(par-assoc-list))(t)(q)  in
     let qual-all-formals = get-qualified-ids(all-formals)(v)  in
      (null(qual-all-formals)
       → (mk-sd
            (z)(ε)(ε)(ε)
            (c(pop-universe(v)(all-formals))(stk-pop(stk)))),
       (no-unbind?
        → (mk-sd
             (z)(ε)(ε)(cons(z,qual-all-formals))
             (cons(mk-cover-already((dot(z),cons(pound(z),qual-all-formals)))(t),
              cons(mk-undeclare(qual-all-formals),
              c(pop-universe(v)(all-formals))(stk-pop(stk))))))),
        let expr1* = actuals  in
         MR [[ expr1* ]](t)(p)(h1)(v)(stk)
         where
         h1 = λ(e1*,f1*),v1,stk1.
                let to-actuals = collect-toargs(underef(e1*))(par-assoc-list)  in
                 let qual-to-actuals = get-qualified-ids(to-actuals)(v1)  in
                  (null(qual-to-actuals)
                   → (mk-sd
                        (z)(ε)(ε)(cons(z,qual-all-formals))
                        (cons(mk-cover-already
                                 ((dot(z),cons(pound(z),qual-all-formals)))(t),
                         cons(mk-undeclare(qual-all-formals),
                         c(pop-universe(v1)(all-formals))(stk-pop(stk1))))))),
```

```
let from-formals = collect-frompars(par-assoc-list)(q)
    and type-descriptors = collect-toargs-types
                              (actuals)(par-assoc-list)(t)(p) in
 let expr2* = from-formals in
  MR [[ expr2* ]] (t)(q)(h2)(v1)(stk1)
  where
  h2 = λ(e2*,f2*),v2,stk2.
         u1(v2)(stk2)
          where
          u1 = λv3,stk3.
                 let guard* = nconc
                                (collect-guards-for-exprs
                                   (from-formals)
                                   (type-descriptors)(t)
                                   (q)(v3)(stk3),f1*,
                                f2*) in
                (mk-sd
                   (z)(guard*)(ε)(qual-to-actuals)
                   (nconc
                      (assign-multiple
                         (qual-to-actuals)
                         (type-descriptors)(e2*),
                      u2(v3)(stk3))))
                 where
                 u2 = λv4,stk4.
                        (mk-sd
                           (z)(ε)(ε)
                           (cons(z,qual-all-formals))
                           (cons(mk-cover-already
                                    ((dot(z),
                                      cons(pound(z),
                                      qual-all-formals)))(t),
                            cons(mk-undeclare
                                    (qual-all-formals),
                            c(pop-universe
                                 (v4)
                                 (all-formals))
                            (stk-pop(stk4)))))))))

underef(actuals)
= (null(actuals)→ ε,
   let actual = hd(actuals) in
    (dotted-expr-p(actual)→ cons(second(actual),underef(tl(actuals))),
     cons(actual,underef(tl(actuals)))))

mk-cover-already(id,lst)(t)
= (new-declarations()→ mk-rel(univint-type-desc(t))((EQ ,hd(lst),id)),
   mk-cover(id,lst))

mk-undeclare(lst) = cons(UNDECLARE ,lst)
```

Procedure calls in Stage 3 VHDL use *call by value-result* semantics. The translation of a procedure call consists of the following steps:

- The actual parameters are translated and then **gen-call** pushes a subprogram return descriptor and then a (single) undeclaration descriptor for all of the formal parameters onto the execution stack.

- SDVS declarations of *all* of the formal parameters are emitted (in **bind-parameters**).
- The `IN` and `INOUT` formal parameters are bound to their corresponding actual parameters by first translating the actual parameters and then in effect assigning them to their corresponding formals by emitting appropriate equality relations (as in the translation of assignment). This is done by auxiliary semantic function **bind-parameters**. In these equality relations, the qualified names of the formal parameters must refer to the procedure's *declaration* TSE, whereas the qualified names in the actual parameters refer to the procedure's *calling* environment. This implements the semantics of *static binding* required by VHDL.
- The subprogram may have either a specific body or a set of state delta characterizations, but not both. Different actions are performed in each case.
  1. If the procedure has a body, the procedure's local declarations and statements are translated in the procedure's *declaration* environment after first pushing a ***SUBPROGRAM-RETURN*** descriptor on the execution stack. This descriptor will be used to perform a return from the procedure, whether that return is explicit via a `RETURN` statement or implicit via encountering the end of the procedure's body.
  2. If the procedure has one or more characterizations, state deltas representing the actions of the procedure are produced by the functions **gen-characterizations** and **gen-characterization**. These two functions use the SDVS functions **fixed-characterized-sds** and **subst-vars**, part of the implementation of an *offline characterization* mechanism for SDVS [3].
- Auxiliary semantic function **unbind-parameters** is invoked to assign the (final) values of the `INOUT` and `OUT` formal parameters to their corresponding actual parameters (which must, of course, have *reference* types).

```
(SS12) SS [[ RETURN atmark opt-expr ]] (t)(p)(c)(v)(stk)
       = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
         let expr = opt-expr in
          R [[ expr ]] (t)(p)(k)(v)(stk)
          where
          k = λ(e,f),v,stk.
                (null(e)→ (mk-sd(hd(p))(ε)(ε)(ε)(return(v)(stk))),
                 let d = context(t)(p) in
                  let result-d = tdesc(extract-rtype(d)) in
                   let precondition = nconc
                                        (mk-constraint-guards
                                            ((e))((result-d))(t)(p)
                                            (v)(stk),f) in
                    (mk-sd
                        (hd(p))(precondition)(ε)
                        ((qualified-id(qid(d))(v)))
                        (nconc
                            (assign(result-d)((qualified-id(qid(d))(v),e)),
                            c1(v)(stk)
                              where c1 = λv,stk.return(v)(stk))))))
```

```
return(v)(stk)
= let <tg,qname,p,g> = hd(stk) in
    (case tg
       *UNDECLARE* → g(λvv,s.return(vv)(s))(v)(stk),
       (*BLOCK-EXIT* ,*SUBPROGRAM-RETURN* ) → g(v)(stk-pop(stk)),
       (*BEGIN* ,*LOOP-EXIT* ,*PACKAGE-BODY-EXIT* ) → return(v)(stk-pop(stk)),
       OTHERWISE
       → impl-error("Bad execution stack descriptor tag in context: ~a",tg))

context(t)(path)
= let d = t(path)(*UNIT* ) in
    (d = *UNBOUND* → context(t)(rest(path)),
     (case tag(d)
        (*PROCEDURE* ,*FUNCTION* ,*PACKAGE* ) → t(rest(path))(last(path)),
        OTHERWISE → context(t)(rest(path))))

extract-rtype(d)
= let signature = hd(signatures(d)) in
    rtype(signature)
```

RETURN statements come in two varieties: *with* an expression, to effect a return from a function, and *without* an expression, to effect a return from a procedure. If the RETURN is from a function, then the expression must first be translated and an assignment of its value to the function's (statically and dynamically uniquely qualified) name must be asserted via an equality relation. Then (no matter whether the RETURN is from a procedure or a function), the function **return** (similar to **exit**) is invoked to use the topmost ***SUBPROGRAM-RETURN*** descriptor on the execution stack to return from the subprogram, after first effecting exits from intervening loops and effecting necessary undeclarations. The function **context** determines the qualified name of the subprogram from which the return is being made.

```
(SS13) SS ⟦ WAIT atmark ref* opt-expr1 opt-expr2 ⟧ (t)(p)(c)(v)(stk)
       = cons((EQ ,pound(catenate(hd(p),"\pc")),atmark),
         let c1 = λv,stk.
                  (mk-sd
                     (hd(p))(ε)(ε)(ε)
                     ((make-vhdl-try-resume-next-process(hd(p))(v)(stk)))) in
          ME ⟦ ref* ⟧ (t)(p)(h)(v)(stk)
           where
           h = λ(e*,f*),v1,stk1.
                 let expr1 = opt-expr1 in
                  R ⟦ expr1 ⟧ (t)(p)(k1)(v)(stk)
                  where
                  k1 = λ(e1,f1),v,stk.
                         let expr2 = opt-expr2 in
                          R ⟦ expr2 ⟧ (t)(p)(k2)(v)(stk)
                          where
                          k2 = λ(e2,f2),v,stk.
                                 let process-id = last(find-process-env
                                                        (t)(p)) in
                                  (mk-sd
                                     (hd(p))(nconc(f1,f2,f*))(ε)(ε)
                                     ((make-vhdl-process-suspend
                                        (process-id)(get-signals(e*))
                                        (e1)(e2)(c)(c1(v)(stk))))))
```

```
find-process-env(t)(p)
= (null(p)∨ tag(t(p)(*UNIT* ))= *PROCESS* → p, find-process-env(t)(rest(p)))

get-signals(signal-names)
= (null(signal-names)→ ε,
   cons(find-signal-structure(hd(signal-names)),get-signals(tl(signal-names))))
```

8.4.7 Waveforms and Transactions

```
(W1) W ⟦ WAVE transaction+ ⟧ (t)(p)(wave-cont)(v)(stk)
     = TRM ⟦ transaction+ ⟧ (t)(p)(wave-cont)(v)(stk)

(TRM0) TRM ⟦ ε ⟧ (t)(p)(wave-cont)(v)(stk) = wave-cont((ε,ε))(v)(stk)

(TRM1) TRM ⟦ transaction transaction* ⟧ (t)(p)(wave-cont)(v)(stk)
       = TR ⟦ transaction ⟧ (t)(p)(trans-cont)(v)(stk)
          where
          trans-cont = λ(trans,guard),v,stk.
                       TRM ⟦ transaction* ⟧ (t)(p)(wave-cont1)(v)(stk)
                        where
                        wave-cont1 = λ(trans*,guard*),v,stk.
                                     wave-cont
                                        ((cons(trans,trans*),
                                          nconc(guard,guard*)))(v)(stk)
```

The transactions in a waveform are translated in order, from left to right.

```
(TR1) TR ⟦ TRANS expr opt-expr ⟧ (t)(p)(trans-cont)(v)(stk)
      = R ⟦ expr ⟧ (t)(p)(k)(v)(stk)
         where
         k = λ(e1,f1),v,stk.
               let expr2 = opt-expr in
                R ⟦ expr2 ⟧ (t)(p)(k1)(v)(stk)
                where
                k1 = λ(e2,f2),v,stk.
                       trans-cont
                          ((mk-transaction-for-update(e1)(e2),nconc(f1,f2)))
                          (v)(stk)

mk-transaction-for-update(transaction-value)(delay-time)
= let transaction-time = (null(delay-time)→ mk-add-delay-time(0)(1),
                          mk-add-delay-time(delay-time)(0)) in
    mk-transaction(transaction-time)(transaction-value)

mk-add-delay-time(global)(delta)
= (TIMEPLUS ,dot(VHDLTIME ),mk-vhdltime(global)(delta))

mk-vhdltime(global)(delta) = (VHDLTIME ,global,delta)
```

8.4.8 Expressions

Two semantic functions, **E** and **R**, translate expressions. **E** obtains the (qualified) *place name* corresponding to a scalar or array. **R** yields an expression that represents a *value* rather than a reference.

(ME0) $\underline{\mathbf{ME}}$ ⟦ ε ⟧ (t)(p)(h)(v)(stk) = h((ε,ε))(v)(stk)

(ME1) $\underline{\mathbf{ME}}$ ⟦ ref ref* ⟧ (t)(p)(h)(v)(stk)
= $\underline{\mathbf{E}}$ ⟦ ref ⟧ (t)(p)(k)(v)(stk)
where
k = λ(e,f),v_1,stk_1.
$\underline{\mathbf{ME}}$ ⟦ ref* ⟧ (t)(p)(h_1)(v_1)(stk_1)
where h_1 = λ(e*,f*),v_2,stk_2.h((cons(e,e*),nconc(f,f*)))(v_2)(stk_2)

(MR0) $\underline{\mathbf{MR}}$ ⟦ ε ⟧ (t)(p)(h)(v)(stk) = h((ε,ε))(v)(stk)

(MR1) $\underline{\mathbf{MR}}$ ⟦ expr expr* ⟧ (t)(p)(h)(v)(stk)
= $\underline{\mathbf{R}}$ ⟦ expr ⟧ (t)(p)(k)(v)(stk)
where
k = λ(e,f),v_1,stk_1.
$\underline{\mathbf{MR}}$ ⟦ expr* ⟧ (t)(p)(h_1)(v_1)(stk_1)
where h_1 = λ(e*,f*),v_2,stk_2.h((cons(e,e*),nconc(f,f*)))(v_2)(stk_2)

The translation of a (possibly empty) multiple expression list yields a list of translated expressions and a corresponding list of guard formulas.

(E1) $\underline{\mathbf{E}}$ ⟦ **REF** modifier$^+$ ⟧ (t)(p)(k)(v)(stk)
= **let** basic-ref = modifier$^+$ **in**
let (basic-name,d) = gen-basic-name(basic-ref)(t)(v) **in**
gen-name(ref)(basic-name)(ε)(d)(tl(basic-ref))(t)(p)(k)(v)(stk)

```
gen-basic-name(basic-ref)(t)(v)
= let (tg,q,id) = hd(basic-ref) in
    let d = t(q)(id) in
     (case tag(d)
        (*PROCEDURE* ,*FUNCTION* ) → (qualified-id(qid(d))(v),d),
        OTHERWISE → (qualified-id(qid(d))(v),tdesc(type(d))))

gen-name(ref)(e)(f)(d)(ref-tail)(t)(p)(k)(v)(stk)
= (null(ref-tail)→ k((e,f))(v)(stk),
   let modifier = hd(ref-tail) in
    let (tg,isp) = modifier in
     (case tg
        INDEX → gen-array-ref(isp)(e)(f)(d)(t)(p)(c)(v)(stk),
        SELECTOR → gen-record-ref(isp)(e)(f)(d)(c)(v)(stk),
        PARLIST → gen-function-call(ref)(isp)(d)(t)(p)(c)(v)(stk),
        OTHERWISE
        → impl-error("Unrecognized Stage 3 VHDL reference modifier tag: ~a",tg))
    where
    c = λ(e1,f1,d1),v,stk.
         gen-name(ref)(e1)(f1)(d1)(tl(ref-tail))(t)(p)(k)(v)(stk))
```

```
gen-array-ref(expr)(e)(f)(d)(t)(p)(c)(v)(stk)
= R [[ expr ]] (t)(p)(k)(v)(stk)
    where
    k = λ(e0,f0),v,stk.
          c(((ELEMENT ,e,e0),
             nconc
                (f,f0,
                (null(ub(d))
                 → (mk-rel(univint-type-desc(t))((GE ,e0,(ORIGIN ,e)))),
                 (mk-rel(univint-type-desc(t))((GE ,e0,(ORIGIN ,e))),
                  mk-rel
                     (univint-type-desc(t))
                     ((LE ,e0,
                        mk-exp2(SUB ,mk-exp2(ADD ,(ORIGIN ,e),(RANGE ,e)),1))))))),
            elty(d)))(v)(stk)

gen-record-ref(id)(e)(f)(d)(c)(v)(stk)
= c((mk-recelt(e,id),f,lookup-record-desc(components(d))(id)))(v)(stk)

mk-recelt(e)(id) = (RECORD ,e,id)

lookup-record-desc(comp*)(id)
= (null(comp*)→ *UNBOUND* ,
   let (x,d) = hd(comp*) in
     (x = id → d, lookup-record-desc(tl(comp*))(id)))

gen-function-call(ref)(expr*)(d)(t)(p)(c)(v)(stk)
= declare-function-name(d)(t)(p)(u)(v)(stk)
    where
    u = λv,stk.
          gen-call(ref)(d)(expr*)(tt)(tt)(t)(p)(c1)(v)(stk)
           where
           c1 = λv,stk.
                 c((qualified-id(qid(d))(v),ε,tdesc(extract-rtype(d))))(v)(stk)

declare-function-name(d)(t)(p)(u)(v)(stk)
= let q = path(d)
      and dd = tdesc(extract-rtype(d)) in
   let z = hd(q) in
    let suqn+ = get-qids((idf(d)))(t)(q) in
     let v1 = push-universe(v)(z)(suqn+) in
      let duqn+ = get-qualified-ids(suqn+)(v1) in
       let dc-desc = <*UNDECLARE* ,idf(d),q,
                          λu1,v2,stk2.
                           undeclare-function-name
                              (suqn+)(duqn+)(z)(t)(u1)(v2)(stk2)> in
         (mk-decl-sd
            (z)(ε)(ε)((z))
            (nconc
               (mk-qual-id-coverings(suqn+)(duqn+)(z)(v)(t),
               mk-scalar-nonsignal-dec-post
                  (ε)((duqn+,ε,dd))(t)(q)(u)(v1)(stk-push(dc-desc)(stk)))))

undeclare-function-name(suqn+)(duqn+)(z)(t)(u)(v)(stk)
= (mk-sd
      (z)(ε)(ε)(cons(z,duqn+))
      (cons(mk-cover-already((dot(z),cons(pound(z),duqn+))))(t),
       cons(mk-undeclare(duqn+),
       u(pop-universe(v)(suqn+))(stk-pop(stk))))))
```

A reference must begin with at least a *basic reference*, which contains its *root identifier* and *access path.* Following its basic reference, a reference has zero or more array index, record field selection, or actual parameter list *modifiers*. The reference itself is translated by **gen-name**; the basic reference is translated by **gen-basic-name**. The array index and record field selection modifiers are translated by **gen-array-ref** and **gen-record-ref**. The translation of a reference is complicated by the appearance of a parameter list modifier, which represents a function call; these are translated by **gen-function-call.**

Whenever a function is called (as part of an expression), the name of that function is used in the expression to name the value returned by that particular invocation. Because the same function can be invoked more than once in the same expression, each corresponding instance of the function's name must be uniquely dynamically qualified, and each of those DUQNs must be declared (and later undeclared when they should no longer exist) to SDVS. The declaration is performed by function **declare-function-name** and the undeclaration by **undeclare-function-name**; the invocation of the latter function is encapsulated in an undeclaration (***UNDECLARE***) descriptor pushed onto the execution stack. After a new dynamic instance of the function's name is declared, **gen-function-call** evaluates the actual parameters and then invokes **gen-call** to finish the translation of this function call.

(R0) $\underline{\mathbf{R}}\ [\![\ \epsilon\ ]\!]\ (t)(p)(k)(v)(stk) = k((\epsilon,\epsilon))(v)(stk)$

For technical convenience, expressions can be empty; the translation of an empty expression yields empty results.

(R1) $\underline{\mathbf{R}}\ [\![\ \mathbf{FALSE}\ ]\!]\ (t)(p)(k)(v)(stk) = k((\mathbf{FALSE}\ ,\epsilon))(v)(stk)$

(R2) $\underline{\mathbf{R}}\ [\![\ \mathbf{TRUE}\ ]\!]\ (t)(p)(k)(v)(stk) = k((\mathbf{TRUE}\ ,\epsilon))(v)(stk)$

(R3) $\underline{\mathbf{R}}\ [\![\ \mathbf{BIT}\ \text{bitlit}\ ]\!]\ (t)(p)(k)(v)(stk) = k((\underline{\mathbf{B}}\ [\![\ \text{bitlit}\ ]\!]\ ,\epsilon))(v)(stk)$

(R4) $\underline{\mathbf{R}}\ [\![\ \mathbf{NUM}\ \text{constant}\ ]\!]\ (t)(p)(k)(v)(stk) = k((\underline{\mathbf{N}}\ [\![\ \text{constant}\ ]\!]\ ,\epsilon))(v)(stk)$

(R5) $\underline{\mathbf{R}}\ [\![\ \mathbf{TIME}\ \text{constant}\ \mathbf{FS}\ ]\!]\ (t)(p)(k)(v)(stk) = k((\underline{\mathbf{N}}\ [\![\ \text{constant}\ ]\!]\ ,\epsilon))(v)(stk)$

(R6) $\underline{\mathbf{R}}\ [\![\ \mathbf{CHAR}\ \text{constant}\ ]\!]\ (t)(p)(k)(v)(stk) = k((expr,\epsilon))(v)(stk)$

(R7) $\underline{\mathbf{R}}\ [\![\ \mathbf{ENUMLIT}\ \text{id}\ ]\!]\ (t)(p)(k)(v)(stk) = k((id,\epsilon))(v)(stk)$

(R8) $\underline{\mathbf{R}}\ [\![\ \mathbf{BITSTR}\ \text{bit-lit}^*\ ]\!]\ (t)(p)(k)(v)(stk)$
$= \mathbf{let}\ \ expr^* = \text{bit-lit}^*\ \ \mathbf{in}$
$\underline{\mathbf{MR}}\ [\![\ expr^*\ ]\!]\ (t)(p)(k)(v)(stk)$

```
(R9) R [[ STR char-lit* ]] (t)(p)(k)(v)(stk)
     = let expr* = char-lit* in
         MR [[ expr* ]] (t)(p)(k)(v)(stk)


(R10) R [[ REF modifier+ ]] (t)(p)(k)(v)(stk)
      = let ref = expr in
          E [[ ref ]] (t)(p)(k1)(v)(stk)
          where k1 = λ(e,f),v1,stk1.k((dot(e),f))(v1)(stk1)
```

Scalar and array references are first **E**-translated, yielding an expression and a guard formula. The corresponding **R**-translation is obtained by applying the **dot** operation to the translated expression.

```
(R11) R [[ PAGGR expr* ]] (t)(p)(k)(v)(stk) = MR [[ expr* ]] (t)(p)(k)(v)(stk)


(R12) R [[ TYPECONV expr type-mark ]] (t)(p)(k)(v)(stk)
      = let d = lookup-desc(type-mark)(t)(p) in
          R [[ expr ]] (t)(p)(k1)(v)(stk)
            where
            k1 = λ(e,f),v,stk.
                   let constraint-guard* = mk-constraint-guards
                                             ((e))((d))(t)(p)(v)(stk) in
                    (null(constraint-guard*)→ k((e,f))(v)(stk),
                     (mk-sd(hd(p))(constraint-guard*)(ε)(ε)(k((e,f))(v)(stk))))


(R13) R [[ unary-op expr ]] (t)(p)(k)(v)(stk)
      = R [[ expr ]] (t)(p)(k1)(v)(stk)
          where k1 = λ(e,f),v1,stk1.k((mk-exp1(unary-op,e),f))(v1)(stk1)

mk-exp1(unary-op,e)
= (case unary-op
     NOT → (NOT ,e),
     BNOT → (USNOT ,e),
     PLUS → e,
     NEG → (MINUS ,e),
     ABS → (ABS ,e),
     (RNEG ,RABS ) → (unary-op,e),
     OTHERWISE
     → impl-error("Unrecognized Stage 3 VHDL unary operator: ~a",unary-op))


(R14) R [[ binary-op expr1 expr2 ]] (t)(p)(k)(v)(stk)
      = R [[ expr1 ]] (t)(p)(k1)(v)(stk)
          where
          k1 = λ(e1,f1,v1,stk1).
                 R [[ expr2 ]] (t)(p)(k2)(v1)(stk1)
                   where
                   k2 = λ(e2,f2),v2,stk2.
                          k((mk-exp2(binary-op,e1,e2),nconc(f1,f2)))(v2)(stk2)
```

(R15) $\underline{\mathbf{R}}$ ⟦ relational-op $expr_1$ $expr_2$ ⟧ (t)(p)(k)(v)(stk)
= $\underline{\mathbf{R}}$ ⟦ $expr_1$ ⟧ (t)(p)(k_1)(v)(stk)
where
k_1 = $\lambda(e_1,f_1,v_1,stk_1)$.
$\underline{\mathbf{R}}$ ⟦ $expr_2$ ⟧ (t)(p)(k_2)(v_1)(stk_1)
where
k_2 = $\lambda(e_2,f_2),v_2,stk_2$.
let d = $\underline{\mathbf{T}}$ ⟦ $expr_1$ ⟧ (t)(p) **in**
k((mk-rel(d)((relational-op,e_1,e_2)),nconc(f_1,f_2)))
(v_2)(stk_2)

8.4.9 Expression Types

The function **mk-rel** (described earlier) requires a type descriptor as its first argument; application of the semantic function **T** determines the type descriptor of an expression as follows:

- if the expression is a constant, its type descriptor is the basic type of that constant;
- if the expression is a reference, its type descriptor is the basic type of that reference, obtained by the function **get-type-desc**; and
- if the expression contains operators, its type descriptor is the basic result type of its top-level operator (if there is one);

(T0) $\underline{\mathbf{T}}$ ⟦ ε ⟧ (t)(p) = void-type-desc(t)

(T1) $\underline{\mathbf{T}}$ ⟦ **FALSE** ⟧ (t)(p) = bool-type-desc(t)

(T2) $\underline{\mathbf{T}}$ ⟦ **TRUE** ⟧ (t)(p) = bool-type-desc(t)

(T3) $\underline{\mathbf{T}}$ ⟦ **BIT** bitlit ⟧ (t)(p) = bit-type-desc(t)

(T4) $\underline{\mathbf{T}}$ ⟦ **NUM** constant ⟧ (t)(p) = univint-type-desc(t)

(T5) $\underline{\mathbf{T}}$ ⟦ **TIME** constant **FS** ⟧ (t)(p) = time-type-desc(t)

(T6) $\underline{\mathbf{T}}$ ⟦ **CHAR** constant ⟧ (t)(p) = char-type-desc(t)

(T7) $\underline{\mathbf{T}}$ ⟦ **ENUMLIT** id ⟧ (t)(p)
= **let** d = lookup-desc-on-path(t)(p)(id) **in**
tdesc(type(d))

(T8) $\underline{\mathbf{T}}$ ⟦ **BITSTR** bit-lit* ⟧ (t)(p) = bitvector-type-desc(t)

(T9) $\underline{\mathbf{T}}$ ⟦ **STR** char-lit* ⟧ (t)(p) = string-type-desc(t)

(T10) $\underline{\mathbf{T}}$ ⟦ **REF** modifier+ ⟧ (t)(p)
= **let** basic-ref = modifier+ **in**
get-type-desc(basic-ref)(t)(p)

```
get-type-desc(basic-ref)(t)(p)
= let (tg,q,id) = hd(basic-ref) in
    let d = t(q)(id) in
     (case tag(d)
        (*PROCEDURE* ,*FUNCTION* ,*PROCESS* )
        → process-ref-tail(d)(tl(basic-ref))(t)(p),
        OTHERWISE → process-ref-tail(tdesc(type(d)))(tl(basic-ref))(t)(p))

process-ref-tail(d)(ref-tail)(t)(p)
= (null(ref-tail)→ d,
   let modifier = hd(ref-tail) in
    (case hd(modifier)
       INDEX → process-ref-tail(elty(d))(tl(ref-tail))(t)(p),
       SELECTOR
       → process-ref-tail
            (lookup-record-desc(components(d))(second(modifier)))(tl(ref-tail))
            (t)(p),
       PARLIST → process-ref-tail(tdesc(extract-rtype(d)))(tl(ref-tail))(t)(p),
       OTHERWISE
       → impl-error
            ("Unrecognized Stage 3 VHDL reference modifier tag: ~a",
            hd(modifier))))
```

(T11) $\underline{\mathbf{T}}$ ⟦ **PAGGR** expr* ⟧ (t)(p) = void-type-desc(t)

(T12) $\underline{\mathbf{T}}$ ⟦ **TYPECONV** expr type-mark ⟧ (t)(p) = lookup-desc(type-mark)(t)(p)

(T13) $\underline{\mathbf{T}}$ ⟦ unary-op expr ⟧ (t)(p) = tdesc(restype1(unary-op)(t))

```
restype1(unary-op)(t)
= (case unary-op
     NOT → (VAL ,bool-type-desc(t)),
     BNOT → (VAL ,bit-type-desc(t)),
     (PLUS ,NEG ,ABS ) → (VAL ,univint-type-desc(t)),
     (RNEG ,RABS ) → (VAL ,real-type-desc(t)),
     OTHERWISE
     → impl-error("Unrecognized Stage 3 VHDL unary operator: ~a",unary-op))
```

(T14) $\underline{\mathbf{T}}$ ⟦ binary-op $expr_1$ $expr_2$ ⟧ (t)(p)
= tdesc(restype2(binary-op)(($expr_1$,$expr_2$))(t)(p))

```
restype2(binary-op)(expr1,expr2)(t)(p)
= (case binary-op
     (AND ,NAND ,OR ,NOR ,XOR ) → mk-type((DUMMY VAL) )(bool-type-desc(t)),
     (BAND ,BNAND ,BOR ,BNOR ,BXOR ) → mk-type((DUMMY VAL) )(bit-type-desc(t)),
     (ADD ,SUB ,MUL ,DIV ,MOD ,REM ,EXP ) → mk-type((DUMMY VAL) )(univint-type-desc(t)),
     (RPLUS ,RMINUS ,RTIMES ,RDIV ,REXPT ) → mk-type((DUMMY VAL) )(real-type-desc(t)),
     CONCAT
     → let d1 = T ⟦ expr1 ⟧ (t)(p)
           and d2 = T ⟦ expr2 ⟧ (t)(p) in
        mk-type((DUMMY VAL) )(mk-concat-tdesc(d1)(d2)(t)),
     OTHERWISE
     → impl-error("Unrecognized Stage 3 VHDL binary operator: ~a",binary-op))
```

```
mk-concat-tdesc(d1)(d2)(t)
= (is-bit-tdesc?(d1)∨ is-bitvector-tdesc?(d1)
   → array-type-desc
        (new-array-type-name(BIT_VECTOR ))(ε)(ε)(tt)(direction(d1))(lb(d1))(ε)
        (bit-type-desc(t)),
   let idf1 = idf(d1) in
    array-type-desc
      (new-array-type-name((consp(idf1)→ hd(idf1), idf1)))(ε)(ε)(tt)
      (direction(d1))(lb(d1))(ε)(elty(d1)))
```

(T15) **T** ⟦ relational-op $expr_1$ $expr_2$ ⟧ (t)(p) = bool-type-desc(t)

8.4.10 Primitive Semantic Equations

The following semantic functions are primitive.

(N1) **N** ⟦ constant ⟧ = constant

(B1) **B** ⟦ bitlit ⟧ = mk-bit-simp-symbol(bitlit)

```
mk-bit-simp-symbol(bitlit)
= (case bitlit
     0 → (BS 0 1) ,
     1 → (BS 1 1) ,
     OTHERWISE → impl-error("Can't construct simp symbol for bit: ~a ",bitlit))
```

9 Conclusion

A precise and well-documented formal specification of the Stage 3 VHDL translator has been presented in this report. We have completed and exercised a Common Lisp implementation of both translation phases described herein.

Stage 3 VHDL represents a robust behavioral subset of the VHSIC Hardware Description Language, encompassing the following VHDL language features: (restricted) design files, entity declarations, architecture bodies, ports, declarative parts in entity declarations, package `STANDARD` (containing predefined types `BOOLEAN`, `BIT`, `UNIVERSAL_INTEGER`, `INTEGER`, `TIME`, `CHARACTER`, `REAL`, `STRING`, and `BIT_VECTOR`), user-defined packages, `USE` clauses, array type declarations, certain predefined attributes, enumeration types, subtypes of scalar types, integer type definitions, type conversions, `PROCESS` statements, concurrent signal assignment statements, subprograms (procedures and functions), `IF` and `CASE` statements, `WHILE` and `FOR` loops, octal and hexadecimal representations of bitstrings, and general expressions of type `TIME` in `AFTER` clauses.

As the SDVS interface to VHDL continues to expand and mature, our confidence grows in our language translator semantic specification and implementation paradigm. In 1994, we will be applying this paradigm to implement a translator for the Stage 4 VHDL language subset. Stage 4 VHDL is expected to include constructs that are needed to verify a VHDL application planned for fiscal year 1994, including structural descriptions (e.g. *component declarations*, *component instantiation statements*, and *configuration declarations*), as well as an implementation of a symbolic VHDL hardware clock.

References

[1] J. V. Cook, I. V. Filippenko, B. H. Levy, L. G. Marcus, and T. K. Menas, "Formal Computer Verification in the State Delta Verification System (SDVS)," in *Proceedings of the AIAA Computing in Aerospace Conference*, (Baltimore, Maryland), pp. 77–87, American Institute of Aeronautics and Astronautics, October 1991.

[2] B. Levy, I. Filippenko, L. Marcus, and T. Menas, "Using the State Delta Verification System (SDVS) for Hardware Verification," in *Proceedings of the IFIP TC10/WG 10.2 International Conference on Theorem Provers in Circuit Design: Theory, Practice and Experience: Nijmegen, The Netherlands* (ed. V. Stavridou, T. F. Melham, and R. T. Boute), pp. 337–360, North-Holland, June 1992.

[3] L. G. Marcus, "SDVS 12 Users' Manual," Technical Report ATR-93(3778)-4, The Aerospace Corporation, September 1993.

[4] T. K. Menas, "SDVS 11 Tutorial," Technical Report ATR-92(2778)-12, The Aerospace Corporation, September 1992.

[5] B. H. Levy, "Feasibility of Hardware Verification Using SDVS," Technical Report ATR-88(3778)-9, The Aerospace Corporation, September 1988.

[6] IEEE, *Standard VHDL Language Reference Manual*, 1988. IEEE Std. 1076-1987.

[7] D. F. Martin and J. V. Cook, "Adding Ada Program Verification Capability to the State Delta Verification System (SDVS)," in *Proceedings of the 11th National Computer Security Conference*, National Bureau of Standards/National Computer Security Center, October 1988.

[8] T. Aiken, I. Filippenko, B. Levy, and D. Martin, "A Formal Description of the Incremental Translation of Core VHDL into State Deltas in the State Delta Verification System (SDVS)," Technical Report ATR-89(4778)-9, The Aerospace Corporation, September 1989.

[9] I. V. Filippenko, "Example Proof of a Core VHDL Description in the State Delta Verification System (SDVS)," Technical Report ATR-90(5778)-6, The Aerospace Corporation, September 1990.

[10] I. V. Filippenko, "Some Examples of Verifying Core VHDL Hardware Descriptions Using the State Delta Verification System (SDVS)," Technical Report ATR-91(6778)-6, The Aerospace Corporation, September 1991.

[11] I. V. Filippenko, "A Formal Description of the Incremental Translation of Stage 1 VHDL into State Deltas in the State Delta Verification System (SDVS)," Technical Report ATR-91(6778)-7, The Aerospace Corporation, September 1991.

[12] M. J. C. Gordon, *The Denotational Description of Programming Languages: An Introduction*, (New York: Springer-Verlag, 1979).

[13] I. V. Filippenko, "A Formal Description of the Incremental Translation of Stage 2 VHDL into State Deltas in the State Delta Verification System (SDVS)," Technical Report ATR-92(2778)-4, The Aerospace Corporation, September 1992.

[14] J. V. Cook, "The Language for DENOTE (Denotational Semantics Translation Environment)," Technical Report TR-0090(5920-07)-2, The Aerospace Corporation, September 1990.

[15] L. Marcus and B. H. Levy, "Specifying and Proving Core VHDL Descriptions in the State Delta Verification System (SDVS)," Technical Report ATR-89(4778)-5, The Aerospace Corporation, September 1989.

[16] L. Marcus, T. Redmond, and S. Shelah, "Completeness of State Deltas," Technical Report ATR-86(8454)-2, The Aerospace Corporation, September 1986.

[17] T. K. Menas, "The Relation of the Temporal Logic of the State Delta Verification System (SDVS) to Classical First-Order Temporal Logic," Technical Report ATR-90(5778)-10, The Aerospace Corporation, September 1990.

[18] J. E. Doner and J. V. Cook, "Offline Characterization of Procedures in the State Delta Verification System (SDVS)," Technical Report ATR-90(8590)-5, The Aerospace Corporation, September 1990.

[19] J. V. Cook and J. E. Doner, "Example Proofs Using Offline Characterization of Procedures in the State Delta Verification System (SDVS)," Technical Report TR-0090(5920-07)-3, The Aerospace Corporation, September 1990.

Index

access 74, 124
already-qualified-id 125
ar1 123
argtypes1 88
argtypes1-error 89
argtypes2 90
argtypes2-error 90
array-signal-assignment 145
array-size 59
array-type 87
array-type-desc 43
art1 54
arx1 95
assign 127, 143
assign-array-downto 128
assign-array-to 128
assign-multiple 157
assign-record 128
assign-record-aux 128
assign-record-fields 128
at0 83
at1 83
at2 83
at3 83
attributes 71
attributes-low-high 63, 139
ax0 99
ax1 99
ax2 99
ax3 99
b1 168
b1 92
base-type 45
bind-parameters 155
bit-type-desc 41
bits-op 103
bitvector-type-desc 42
block-exit 121
body 45
bool-type-desc 41
cascade-array-signal-assignment 145
case-coverage 78
case-overlap 83
case-type-ok 78
case-union 84
char-type-desc 42
characterizations 45
check-array-aggregate 62
check-enum-lits 63
check-exprs 62
check-if 77
check-pkg-names 68
check-wait-ref 83
check-wait-refs 82
chk-array-type 87
collect-allpars 155
collect-expressions-from-conditional-waveforms 74
collect-expressions-from-selected-waveforms 73
collect-fids 66
collect-formal-pars 66
collect-fromargs 156
collect-frompars 156
collect-guards-for-exprs 156
collect-signals-from-expr 73
collect-signals-from-expr-list 73
collect-toargs 156
collect-toargs-types 156
collect-topars 156
collect-topars-types 156
collect-transaction-expressions 73
compatible-par-types 58
compatible-signatures 58
components 46
concatenate-bits 133
concatenate-characters 133
construct-case-alternatives 74
construct-cond-parts 75
context 82, 160
cs0 141
cs1 141
cs2 142
cst0 72
cst1 72
cst2 72

cst3 73
cst4 74
csx0 97
csx1 97
csx2 97
csx3 97
csx4 98
d0 123
d1 123
d10 140
d11 140
d12 140
d13 140
d14 140
d15 141
d16 141
d2 123
d3 123
d4 123
d5 124
d6 124
d7 139
d8 139
d9 140
declare-function-name 163
df1 117
dft1 52
dfx1 95
direction 45
dot 115
dotted-expr-p 119, 127
drt0 84
drt1 84
drt2 84
drx0 99
drx1 99
drx2 99
dt0 55
dt1 55
dt10 64
dt11 65
dt12 65
dt13 67
dt14 67
dt15 71
dt16 72
dt2 55
dt3 55
dt4 55
dt5 55
dt6 61
dt7 63
dt8 63
dt9 64
dx0 96
dx1 96
dx10 96
dx11 96
dx12 96
dx13 96
dx14 97
dx15 97
dx16 97
dx2 96
dx3 96
dx4 96
dx5 96
dx6 96
dx7 96
dx8 96
dx9 96
e1 162
elty 45
en1 122
ent1 53
enter-array-objects 62
enter-characters 53
enter-formal-pars 66
enter-objects 53
enter-package 52
enter-predefined 53
enter-standard 52
enter-string 53
enum-le 92
enum-lt 92
enx1 95
et0 86
et1 86
et10 88
et11 88
et12 88
et13 88

et2 86
et3 86
et4 86
et5 87
et6 87
et7 87
et8 87
et9 87
eval-expr 115
ex0 100
ex1 100
ex10 102
ex11 102
ex12 102
ex13 102
ex2 100
ex3 100
ex4 100
ex5 100
ex6 100
ex7 100
ex8 100
ex9 100
exit 153
export-qualified-names 69
exported 45
extract-par-types 58
extract-pars 155
extract-poly-pars 155
extract-rtype 58, 160
extract-rtypes 82
fifth 14
filter-components 59
find-architecture-env 73
find-looplabel-env 80
find-process-env 76, 161
find-progunit-env 56
find-signal-structure 114
fixed-characterized-sds 115
fourth 14
gen-alt 147
gen-array-decl 130
gen-array-decl-id* 131
gen-array-decl-id+ 130
gen-array-nonsignal-decl-id+ 132
gen-array-ref 163
gen-array-signal-decl-id+ 134
gen-ascending-indices 145
gen-basic-name 162
gen-call 154
gen-case 147
gen-characterization 155
gen-characterizations 154
gen-characters 53
gen-descending-indices 145
gen-function-call 163
gen-guard 148
gen-if 146
gen-name 162
gen-record-ref 163
gen-scalar-decl 124
gen-scalar-decl-id* 124
gen-scalar-decl-id+ 124
gen-scalar-nonsignal-decl-id+ 124
gen-scalar-signal-decl-id+ 129
get-base-type 46, 59
get-loop-enum-param-vals 115
get-parent-type 46
get-qids 125
get-qualified-ids 111, 125
get-signals 161
get-type-desc 167
idf 45
import-legal 69
import-qualified-names 68
init-array-signal-downto 115
init-array-signal-to 115
init-scalar-signal 114
init-var 111
int-type-desc 41
invert-bit 89
is-array-tdesc? 44
is-array? 44
is-binary-op? 46
is-bit-tdesc? 43
is-bit? 43
is-bitvector-tdesc? 44
is-bitvector? 44
is-boolean-tdesc? 43
is-boolean? 43
is-character-tdesc? 44
is-character? 44

is-const? 44, 46
is-constant-bitvector? 119, 127
is-constant-string? 119, 127
is-integer-tdesc? 43
is-integer? 43
is-paggr? 46
is-poly-tdesc? 44
is-poly? 44
is-readable? 46
is-real-tdesc? 43
is-real? 43
is-record-tdesc? 44
is-record? 44
is-ref? 46
is-relational-op? 46
is-sig? 45, 46
is-string-tdesc? 44
is-string? 44
is-time-tdesc? 44
is-time? 44
is-unary-op? 46
is-var? 44, 46
is-void-tdesc? 44
is-void? 44
is-writable? 46
last 15
lb 45
length 15
length-expr 132
list-type 58
literals 45
lookup-desc 124
lookup-desc-for-ref 74
lookup-desc-on-path 74, 124
lookup-local 58
lookup-record-desc 163
lookup-record-field 58
lookup-type 56
lookup2 57
loop-for-enum 152
loop-for-int 151
loop-infinite 149
loop-while 149
make-universe-data 110
make-vhdl-begin-model-execution 114
make-vhdl-process-elaborate 114
make-vhdl-process-suspend 114
make-vhdl-try-resume-next-process 114
match-array-type-names 59
match-integer-types 59
match-type-names 59
match-types 59
me0 162
me1 162
mex0 100
mex1 100
mk-add-delay-time 161
mk-array-decl 133
mk-array-elt 133
mk-array-nonsignal-dec-post 132
mk-array-nonsignal-dec-post-declare 132
mk-array-nonsignal-dec-post-init-downto 133
mk-array-nonsignal-dec-post-init-to 133
mk-array-refs 145
mk-array-refs-aux 145
mk-array-signal-dec-post 135
mk-array-signal-dec-post-declare 135
mk-array-signal-dec-post-init 136
mk-array-signal-dec-post-init-aux 138
mk-array-signal-dec-post-init-downto 137
mk-array-signal-dec-post-init-elt-arrays-downto 138
mk-array-signal-dec-post-init-elt-arrays-to 137
mk-array-signal-dec-post-init-elt-scalars-downto 139
mk-array-signal-dec-post-init-elt-scalars-to 138
mk-array-signal-dec-post-init-to 137
mk-array-signal-decl 135
mk-array-signal-elt-fn-decls 136
mk-array-signal-elt-fn-decls-aux 136
mk-bit-simp-symbol 89, 168
mk-bitvec-fn-decl 133
mk-bool-eq 121
mk-bool-neq 121
mk-concat-tdesc 91, 168
mk-constraint-guards 157
mk-cover 117
mk-cover-already 158
mk-disjoint 117
mk-dotted-names 133

mk-element-transaction-lists 146
mk-element-waves 146
mk-element-waves-aux 115
mk-enum-set 85
mk-enumlit-rels 139
mk-etdec-post 139
mk-exp1 165
mk-exp2 128
mk-inertial-update 145
mk-initial-universe 110
mk-not 145
mk-or 147
mk-ors 147
mk-par-decls 157
mk-preemption 145
mk-qual-id-coverings 125
mk-recelt 129, 163
mk-rel 119
mk-scalar-decl 117, 126
mk-scalar-nonsignal-dec-post 125
mk-scalar-nonsignal-dec-post-declare 126
mk-scalar-nonsignal-dec-post-init 126
mk-scalar-rel 120
mk-scalar-signal-assignments 145
mk-scalar-signal-dec-post 129
mk-scalar-signal-dec-post-declare 129
mk-scalar-signal-dec-post-init 130
mk-scalar-signal-decl 129
mk-scalar-signal-fn-decl 130
mk-scalar-signal-fn-decls 136
mk-set 85
mk-simultaneous-transactions 146
mk-slice-elt-names-downto 133
mk-slice-elt-names-to 133
mk-string-fn-decl 133
mk-tick-high 63, 130, 139
mk-tick-low 63, 130, 139
mk-tmode 46
mk-transaction-for-update 161
mk-transaction-list 146
mk-transport-update 145
mk-type 46
mk-type-spec 126
mk-undeclare 158
mk-vhdl-array-decl 132
mk-vhdltime 121, 161
mk-waveform-type-spec 135
model-execution-complete 121
mr0 162
mr1 162
n1 168
n1 92
name-driver 114
name-drivers 129
name-qualified-id 111, 125
name-type 57
namef 45
next-var 111
nth-tl 85
object-class 46
ot1.1 88
ot2.1 89
ot2.2 89
parent-type 45
pars 46
path 45
pbody 45
pdt0 54
pdt1 54
pdt2 54
pdt3 55
pdx0 95
pdx1 95
pdx2 95
pdx3 95
pkg-body-exit 140
poly-type-desc 42
pop-universe 111
pop-universe-vars 111
pop-var 111
position 85
position-aux 85
pound 115
process 45
process-dec 59
process-ref-tail 167
process-slcdec 61
process-subprog-body 67
process-use-clause 68
push-universe 110
push-universe-vars 110
push-var 111

qid 45
qualified-id 111, 125
qualified-id-decls 125
r0 164
r1 164
r10 165
r11 165
r12 165
r13 165
r14 165
r15 166
r2 164
r3 164
r4 164
r5 164
r6 164
r7 164
r8 164
r9 165
real-lb 130
real-op 103
real-type-desc 42
real-ub 130
record-to-type 126
ref-mode 46
remove-enclosing-pkgs 68
rest 15
restype1 89, 167
restype2 91, 167
resval1 89, 92
return 160
reverse 85
reverse-aux 85
rt1 88
rtype 46
rx1 103
scalar-op 102
scalar-signal-assignment 145
second 14
set-card 78
signatures 45
simple-name-match 69
simple-term 121
sixth 15
slt0 75
slt1 75
slt2 75
slx0 98
slx1 98
slx2 98
ss0 142
ss1 142
ss10 153
ss11 153
ss12 159
ss13 160
ss2 142
ss3 142
ss4 144
ss5 146
ss6 147
ss7 149
ss8 149
ss9 150
sst0 75
sst1 75
sst10 81
sst11 81
sst12 81
sst13 82
sst2 75
sst3 76
sst4 77
sst5 77
sst6 77
sst7 79
sst8 79
sst9 80
ssx1 98
ssx10 99
ssx11 99
ssx12 99
ssx13 99
ssx2 98
ssx3 98
ssx4 98
ssx5 98
ssx6 98
ssx7 98
ssx8 99
ssx9 99
string-type-desc 42

subst-vars 115
t0 166
t1 166
t10 166
t11 167
t12 167
t13 167
t14 167
t15 168
t2 166
t3 166
t4 166
t5 166
t6 166
t7 166
t8 166
t9 166
tag 45
tdesc 46
third 14
time-type-desc 42
tmode 46
tr1 161
transform-if 98
transform-list 102
transform-name 101
transform-name-aux 102
trm0 161
trm1 161
trt1 86
trt2 86
trx1 100
trx2 100
type 45
type-tick-high 45
type-tick-low 45
ub 45
unbind-parameters 158
undeclare-function-name 164
underef 158
universe-counter 110
universe-name 110
universe-stack 110
universe-vars 110
univint-type-desc 41
validate-access 57
value 45
vhdltime-type-desc 117
void-type-desc 42
w1 161
waveform-type-desc 130, 145
wt1 85
wx1 100